The chronology and hydrometeorology of catastrophic floods on Dartmoor, South West England

Foulds, Simon Andrew; Macklin, Mark; Brewer, Paul

Published in:
Hydrological Processes

DOI:
10.1002/hyp.9853

Publication date:
2014

Citation for published version (APA):
Foulds, S. A., Macklin, M., & Brewer, P. (2014). The chronology and hydrometeorology of catastrophic floods on Dartmoor, South West England. *Hydrological Processes*, *28*(7), 3067-3087. https://doi.org/10.1002/hyp.9853

The chronology and hydrometeorology of catastrophic floods on Dartmoor, southwest England

S.A. Foulds[*1], M.G. Macklin[1] and P. A. Brewer[1]

[1]Institute of Geography and Earth Sciences

Llandinam Building

Aberystwyth University

Aberystwyth

Wales, UK

SY23 3DB

+44 (0) 1970 622580

*corresponding author: sif3@aber.ac.uk

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/hyp9853

Abstract

Extreme floods are the most widespread and often the most fatal type of natural hazard experienced in Europe, particularly in upland and mountainous areas. These 'flash flood' type events are particularly dangerous because extreme rainfall totals in a short space of time can lead to very high flow velocities and little or no time for flood warning. Given the danger posed by extreme floods, there are concerns that catastrophic hydrometeorological events could become more frequent in a warming world. However, analysis of longer-term flood frequency is often limited by the use of short instrumental flow records (last 30-40 years) that do not adequately cover alternating flood-rich and flood-poor periods over the last 2-3 centuries. In contrast, this research extends the upland flood series of southwest England (Dartmoor) back to ca. AD 1800 using lichenometry. Results show the period 1820 – mid-1940s was characterised by widespread flooding, with particularly large and frequent events in the mid-to-late 19th and early 20th centuries. Since ca. 1850-1900 there has been a general decline in flood magnitude that was particularly marked after the 1930s/mid-1940s. Local meteorological records show that 1): historical flood-rich periods on Dartmoor were associated with high annual, seasonal and daily rainfall totals in the last quarter of the 19th century and between 1910 and 1946, related to sub-decadal variability of the NAO and receipt of cyclonic and southerly weather types over the southwest peninsula, and 2): the incidence of heavy daily rainfall declined notably after 1946, similar to sedimentary archives of flooding. The peak period of flooding on Dartmoor predates the beginning of gauged flow records, which has practical implications for understanding and managing flood risk on rivers that drain Dartmoor.

Keywords

Flash floods; flood risk management; lichenometry; North Atlantic Oscillation; Dartmoor

INTRODUCTION

Extreme floods represent a combination of severe meteorological and hydrological conditions. These catastrophic events are usually associated with near-stationary storms capable of delivering >100 mm of rainfall in a short period of time (Gaume et al., 2009), typically 2-5 hours. Due to short lag times, high flow velocities and limited time for warning, flood impacts can be devastating, often leading to loss of life, as well as causing significant economic impacts and damage to infrastructure (Guttierez et al., 1998; Delrieu et al., 2005; Gaume et al., 2004, 2009; Barredo 2007; Norbiato at el., 2007; Marchi et al., 2010). Such severe storms are usually convective in origin and tend to affect small upland catchments in the UK and Ireland, typically <25 km^2 (Dobie and Wolf, 1953; Carling, 1986; Acreman, 1989, 1991; Coxon et al., 1989; Macklin et al., 1992; Macklin, 1997; Merrett and Macklin, 1999; Cargill et al., 2004; Macklin and Rumsby, 2007; Roca and Davison, 2009). Given the danger posed by these types of catastrophic event, there are concerns that extreme hydrometeorological events could become more frequent as average global temperatures rise, leading to intensification of the hydrological cycle (Huntingdon, 2006; Pall et al., 2011).

However, answering questions about changing flood frequency and magnitude requires sufficiently long records of fluvial activity. In this respect, although recent European data compilations (e.g. Gaume et al., 2009; Marchi et al., 2010) are important in elucidating the hydrological and meteorological characteristics of severe flood events, their short timescales, which are constrained by the use of recent events and instrumental hydrological and meteorological data series (last 30-40 years), makes analysis of temporal trends difficult, particularly as the majority of steepland catchments where flash floods are common are ungauged. For example, the flash flood data compilation of Gaume et al., (2009) details European fluvial and debris flow frequency data which has an average temporal coverage of 34 years. Likewise, flood data presented by Marchi et al., (2010) covers 14 years, whilst Barredo's (2007) database begins in 1950. In the UK, similar problems have led to a bias of examining relatively short flow records from gauged sites which often show limited evidence of temporal trends over such short periods (Robson, 2002). Although Hannaford and Marsh (2008) demonstrated significant upward flow trends in northern and western Britain, their analysis was based on relatively short (34-44 years) records. This is important because longer-term records are needed to separate long-term trends from short-term variation (Rumsby and Macklin, 1994; Longfield and Macklin, 1999), as well as identifying clustering during alternating flood-rich – flood-poor periods. Indeed, the last 2-3 centuries have been characterised by the appreciable climatic variability of the Little Ice Age and recent anthropogenic global warming. It is, therefore, important to understand present day flood risk with reference to historical climate change.

Alternative approaches to analysis of gauged data involve extending the flood series using documentary/historical data (Macdonald and Black, 2010; Macdonald, 2012; Pattison and Lane, 2012) and geomorphological-sedimentological methods (Macklin et al., 1992; Merrett and Macklin, 1999; Johnson and Warburton, 2002; Macklin and Rumsby, 2007; Gob et al., 2003, 2008, 2010). The latter approach has been widely used in upland catchments in the UK and involves: (1) identification of boulder-berm deposits characteristic of extreme upland floods; (2) flood frequency estimation using lichenometry; and (3) evaluation of relative magnitude based on boulder dimensions. Macklin et al., (1992) first applied this technique in the northern Pennine uplands of the UK. Subsequent studies in the Yorkshire Dales (Merrett and Macklin 1999), Brecon Beacons (Macklin and Rumsby 2007), Lake District (Johnson and Warburton, 2002), steepland Mediterranean catchments (Maas and Macklin, 2002; Gob et al., 2003, 2008, 2010) and South America (Maas et al., 2001) have served to confirm that lichenometry can significantly extend the record of extreme floods, in the order of 200-300 years, as well as identifying underlying climatic controls associated with sub-decadal scale variability of the NAO and ENSO. These findings are important for placing short-term flow records in a more robust temporal context. Furthermore, relative flood magnitude, based on boulder dimensions, often shows that historical upland events (17^{th}-19^{th} centuries) were appreciably larger than 20^{th} century floods (although the latter appear to have been more frequent in many systems (Rumsby and Macklin, 2007)), which has practical implications for flood risk management, especially where valley floors have been impounded. The most common cause of dam wall failures and overtopping is inadequate overspill design (Acreman, 1989) and it is significant that recent summer flash floods in the UK have caused serious damage to masonry spillways (Mason and Hinks, 2008; Walker, 2008).

Although a significant amount of research has been focused on extreme floods in the British uplands since the 1990s, most of this work has been directed towards northern England and Wales (Macklin et al., 1992; Merrett and Macklin, 1999; Johnson and Warburton, 2002; Macklin and Rumsby, 2007; Watkins and Whyte, 2008; Milan, 2012). However, several recent summer flash floods have occurred in southwest England (Table 1), but there are no longer-term data to evaluate the magnitude and frequency of large floods in this region. This is particularly important in the light of climate change and increased flood risk in upland/upland fringe communities that may be particularly vulnerable to extreme flood events (Lewin and Macklin, 2010).

The primary aim of this paper is to construct a high resolution record of flood activity on Dartmoor over the last ca. 150-200 years using lichenometry. Extending the flood record in this way has two clear benefits. First, it enables recent devastating floods in the southwest of England to be placed in a more meaningful temporal context, which short-term instrumental data cannot provide. Second, possible climatic controls can be evaluated, which is particularly important in linking past flood episodes to future projections of climate change and its impact on river valleys and their communities in the UK.

STUDY AREA

Dartmoor is situated on the southwest peninsula of the UK, forming the most extensive upland area in southern Britain (Figure 1) and representing the eastern most pluton of the Cornubian batholith (Chen et al., 1993). Mineralisation and subsequent erosion of the granite surface led to the formation of extensive tin (Sn) placer deposits (Beer and Scrivener, 1982) in wide, lower gradient valley floors. As a result, fine-grained sediment on Dartmoor has been historically 'streamed' for tin (peak production in the 13th and 15th-16th centuries (Thorndycraft et al., 2004)). Boulder-berm deposits were differentiated from mine waste based on differences in sedimentology, geomorphology and location. Typically, streaming sites are located where sand and gravel has accumulated in wide, shallow valley bottoms. Boulder-berms, on the other hand, tend to be restricted to steep and confined gorge sections (Table 2) where rivers leave the granite interior of Dartmoor and cross the softer rocks of the metamorphic aureole. Typically, boulder-berms form expansion bars (Cenderelli and Cluer, 1998) at the terminus of steep gorges and cascades. These extreme flood deposits are orientated on their b-axis', very well imbricated and dip steeply upstream. Boulder-sized material in river channels and on hillslopes is abundant in headwater catchments on Dartmoor, sourced from relict periglacial (Ballantyne and Harris, 1994) and possibly glacial deposits (Evans et al., 2012) that fringe many river channels.

The present climate of Dartmoor is maritime temperate, typified by mild, wet winters and generally cool, cloudy summers. Mean annual temperature at Princetown (453 m AOD) is 8.1^{O}C and mean annual precipitation is 2058 mm (Burt and Holden 2010).

Figure 1 shows the location of study catchments which range from 0.2 to 24.3 km^2 (mean size 5.7 km^2) in size. Table 2 shows summary morphological catchment characteristics and details of flood record length indicated by boulder-berms. A problem when using lichen dating on Dartmoor is the presence of dense vegetation which prevents lichen from growing on boulder-berms. As a result, the majority of study reaches contain a number of flood deposits that cannot be dated using lichenometry (Table 2). These berms are usually situated on terraces which lie above the level of flood deposits dating to the early 19th century.

METHODS AND DATA

Lichenometry is a standard technique for dating coarse-grained flood material in the UK deposited within the last 200-250 years (Macklin et al., 1992; Merrett and Macklin, 1999; Macklin and Rumsby, 2007). The most commonly used method is indirect dating, which relates the size of lichen growing on surfaces of unknown age to growth rates derived for the same lichen and lithology on surfaces of known age (e.g. gravestones). In the present study, four common species (*Porpidia tuberculosa* (Figure 2a), *Rhizocarpon geographicum* (Figure 2b), *Pertusaria corallina* and *Pertusaria aspergilla* (Figure 2c)) were selected to date flood deposits. Both species of *Pertusaria* were found to have similar size-age relationships; these data were combined to provide better temporal coverage (Figure 2c). It was necessary to use several species of lichen because a single species was not consistently present on all boulder-berm units. In total, 15 graveyards and 4 granite structures of known age were used to construct lichen size-age relationships giving a total of 173 individual measurements on control surfaces. Diametral growth rates, corrected for lag colonization periods, are 0.2-0.5 mm yr^{-1} for *Rhizocarpon geographicum*, 0.7 -1.3 mm yr^{-1} for *Porpidia tuberculosa* and 0.7-2.0 mm yr^{-1} for *Pertusaria* species, consistent with published rates for these species (Armstrong and Bradwell, 2010).

The single largest specimen per boulder-berm unit was used for dating (Bradwell, 2009). To test the accuracy and reliability of this method, a second, independent batch of lichen measurements was collected from gravestones (Table 3) and berms of known age (either photographed or described during/shortly after the event (Figure 3)). Regression equations shown in Figure 2 were then rearranged and used to predict surface age, which could then be compared to the true age (Table 3). Most predictions are accurate to $\pm$ 10 years of the observed age, with some accurate to within 1-2 years. The coefficient of correlation between observed and predicted surface age is $r = 0.96$. A small number of predictions deviate in the order of 16-23 years from the true gravestone age and probably relate to variable colonisation rates, local micro-climatic conditions, competition, nutrient enrichment and inadvertent measurement of coalesced specimens. Although test data show a good level of accuracy, there is a statistically significant correlation ($r = 0.394$, $p = 0.023$) between true (observed) surface age and dating error (i.e. error increases with increasing lichen age/size, as reported by other workers (Gob et al., 2008)). This means that dates of the oldest berms are indicative only, and may be accurate to ca. 15-25 years, rather than <10 years for more recent deposits.

To estimate the relative magnitude of flood events, b-axis measurements were made on the three largest boulders within a flood deposit using a tape measure. Although boulder size gives an approximation of relative magnitude, the quantity and size of flood sediment is closely linked to sediment supply, which can be affected by channel incision and slope-channel (de)coupling. There is limited evidence of incision related to 19th and 20th century flood deposits on Dartmoor, although there is clear evidence of terraced berms that predate the early 1800s and this phase of incision may have caused a reduction in sediment supply as river channels became ensconced within their own valley fills (cf. Macklin et al., 1992). Channel bed characteristics, such as grain shape, imbrication, shielding, armouring and protrusion effects related to large boulders, can also cause flood-to-flood variations in sediment entrainment and availability (Costa, 1983; Wohl, 1992; Lenzi et al., 2006). Threshold conditions for particle motion are larger for beds with tight packing and poor sorting and high sediment loads can increase fluid density thus decreasing threshold motion values (Costa, 1983). All of these factors mean that boulder dimensions and inferred flood magnitude on Dartmoor are approximations only.

A documentary flood history was compiled from topographical texts, journals, the Chronology of British Hydrological Events database (www.dundee.ac.uk/geography/cbhe) and the Dartmoor Archive (www.dartmoorarchive.org), allowing comparisons to be made between known floods (Table 4) and the geomorphological record. An important caveat is that only events near populated areas tend to be recorded, and extreme events are quickly forgotten, with the most floods often described as the 'worst in living memory' (Rodda et al., 2009). Considerable caution should also be exercised when comparing documented flood dates with geomorphological records. Because documentary data give little or no reliable information regarding event magnitude, a flood that has been recorded in documentary sources need not necessarily have been geomorphologically effective. Phrases such as ‘unprecedented’, ‘biggest in living memory’ and ‘great flood’ are common in textual flood references on Dartmoor. As shown by recent floods in the UK (Foulds et al., 2012) statements of this nature are often misleading. Indeed, Worth’s (1939) photographs of what he termed a ‘great flood’ on Dartmoor in 1938 show a relatively unspectacular overbank event. Documentary floods can also be mis-dated. Table 4 details a flood that could have occurred in1956 or 1965. Despite the fact that the resulting boulder-berm was photographed, the true flood date is unknown.

Meteorological and climatological data

To allow examination of the sedimentary archive in relation to rainfall and underlying climatic control of the NAO, several data sources have been used. Rainfall records from Holne and Ashburton on southeast Dartmoor, as well as various records from Princetown, located in central Dartmoor (Figure 1), were selected as these are the longest upland rainfall series in the area. The record from Holne is particularly valuable as it covers the relatively early period 1876-1945 and the village lies in a markedly wet zone of considerable interest (Worth, 1924). Data from Holne (and some early records from Princetown) are available in annual meteorological tables presented in *Reports and Transactions of the Devonshire Association*. Twentieth century rainfall data from Princetown were downloaded from the British Atmospheric Data Centre (www.badc.ac.uk).

Despite excellent rainfall data coverage, there are two important limitations of these data that need to be considered when making comparisons with sedimentary flood records. First, short duration (ca. 3-6 hours) rainfall totals, related to high intensity storms, are critical to understanding the magnitude and frequency of geomorphologically effective floods in small upland catchments (e.g. Carling, 1986). These extreme events lead to high bed shear stress and promote slope erosion (gullies and landslides), which in turn affects sediment supply. Historical daily rainfall totals do not record these short duration events. A flood in 1930 on Dartmoor (Table 4) provides an example of this kind. As noted by Worth (1931) daily falls of 50-68 mm are far from unusual on Dartmoor, yet this event appears to have been unusually intense, accounting for the resulting flood. Despite the absence of short duration (sub-daily) rainfall data, we refer to periods of heavy daily rainfall as the most likely in producing boulder-berms in the uplands. Second, localised intense storms are likely to have bypassed rain gauges (e.g. the thunderstorm and flash flood of 1917, which caused berm deposition on Dartmoor, escaped all recording stations (Worth, 1918)). These factors should be considered when interpreting the results of this research as it means that rainfall and sedimentary records are unlikely to be an exact match.

Underlying climatic controls on rainfall have been examined by analysing seasonal trends in the summer and autumn/winter NAO. The winter NAO is based on the Gibraltar-Iceland series, which is most applicable to the October-March period (Osborn, 2006) (series begins 1821). For other seasons, data based on gridded sea level pressure anomalies, which track seasonal movements of the Icelandic low and Azores high over the Atlantic, have been used. For July and August we have used the 'high summer' NAO index of Folland et al., (2009) (series begins in 1850), and for other months we have used the principal component index of the National Centre for Atmospheric Research (www.climatedataguide.ucar.edu) (Hurrell, 1995 - series begins 1899)).

RESULTS

Boulder-berm flood histories on Dartmoor

Figure 4 shows the magnitude of historical floods based on maximum and average boulder dimensions and Figure 5 shows the frequency of berm sedimentation. These data show that 1): the largest dated floods in catchments of all size occurred between ca. 1850 and ca. 1910 (Figure 4), and 2): periods of high (low) flood magnitude tend to correspond with periods of high (low) berm sedimentation (Figure 4, Figure 5). The exception to this pattern is found in small catchments, where the largest dated floods appear to have occurred around the mid-to-late 19th century, compared to peak berm sedimentation in the early 20th century (ca. 1910s/1920s, Figure 5a). The sedimentary record of small rivers is also skewed towards the first half of the 20th century, which agrees with a number of documentary floods at this time, especially the August 1917 event, which affected many small catchments (Worth, 1918; Table 4). There is little geomorphic evidence of 19th century flood episodes in small catchments, consistent with high rates of valley floor reworking and reduced preservation potential of older sediment units in these narrow valleys (Lewin and Macklin, 2003). In these small catchments the most recent geomorphologically effective flood ‘zeroes’ the sedimentary archive.

High rates of berm sedimentation began earlier in medium and large catchments (ca. early-to-mid 19th century) and boulder-berms dating to this period are generally more common (Figure 4c-4f, 5b-5c), consistent with wider valley floors (Table 2) and greater preservation potential. Although high rates of berm sedimentation continued into the early 20th century in medium and large catchments, by the ca. mid-1900s, magnitude and frequency were generally low or decreasing (Figure 4c-4f, 5b-5c). This trend is apparent in all catchments, but especially so in systems that drain >10 km^2 and particularly from 1930 to present (Figure 4, Figure 5). Although flood magnitude was generally declining towards the 20th century, there appears to have been a very severe flood on the River Tavy (Table 2, Table 4; Figure 4e, 4f) in the late 19th/early 20th century. This is consistent with documentary evidence (photographs and written accounts) of an exceptional flood on the River Tavy in 1890 that destroyed numerous bridges and appears to have been one of the most severe historical events on parts of Dartmoor (Table 4). At the turn of the 19th century there were also two other notable floods (November 1894 and February 1900; Table 4) that appear to have been of similar or greater magnitude to 1890 on some rivers.

The decline in geomorphic activity in the early-to-mid 20th century is one of the most notable features of the Dartmoor flood record. The break point in small and medium sized catchments is ca. 1960-1970 (Figures 4a-4d, 5a-5b), while in catchments >10 km^2 in size the cut-off is especially marked and dates to ca. 1930 (Figure 4e, 4f, 5c), although there is a second cluster of berm sedimentation from ca. 1940 to ca. 1990 (albeit of significantly reduced magnitude). An important caveat is that many rivers on Dartmoor have boulder beds and it is possible that lower magnitude 20th century floods may have entrained boulder-sized material as bed-load without producing berms. For example, a documentary flood on the River Avon in 1944 (Table 4) reportedly moved boulders. A survey of this watercourse could not identify any berms, despite the presence of large clasts in the channel bed. High flows in August 2004 on Red-a-ven Brook (Horsham, 2012a) also moved bedload but failed to remobilise 1917 boulder-berm deposits.

In total, 142 boulder-berms have been dated on Dartmoor and aggregating data from catchments of all size highlights the period from 1820 to 1930 as the most geomorphologically active (Figure 5d). This 110 year period covers a series of notable documentary flood events in the 1840s, 1870s, 1880s, 1890s and early 20th century (Table 4; Figure 5e). However, there were a series of documented floods in the 1930s and 1940s (Table 4). Due to typical lichen dating errors (Table 3) it is possible that the age of berms related to these floods may have been overestimated. If this is the case, the drop-off in geomorphological activity may date to the ca. 1940s, rather than ca. 1930. It is also difficult to reconstruct flood activity at sites where vegetated/over-grown boulder-berms lie on terraces above the level of flood units dated to the early 19th century. These features cannot be dated by lichenometry and this period of low data quality is shown on Figures 4 and 5. However, several age estimates have been made on berms that have remained clear of dense vegetation. On the River East Okement, a berm ca. 3-4 m above the modern river level was dated to 1804. Berms on terraces of an unnamed tributary of the River Tavy and Black-a-ven Brook produced lichen ages of 1785 and 1726, respectively. These dates agree with some of the earliest documented floods on Dartmoor (Table 4) and represent older terraced flood deposits associated with an earlier phase of high geomorphic activity and flood crises on Dartmoor.

Meteorological and climatological controls on Dartmoor floods

In the light of evidence of high geomorphic and hydrological activity on Dartmoor from 1820-1930/1940s, instrumental data have been analysed to examine climatic controls on flood frequency and magnitude. In terms of rainfall, there are distinct seasonal relationships with the NAO. During the winter half year (October-March) historical rainfall totals and number of wet days (1876-1945) are positively correlated with the Gibraltar-Iceland NAO index (Figure 6a, 6c, Figure 7b, 7c) and tend to be associated with cyclonic and southerly weather types (Figure 8b, 8c). During the summer months this changes and rainfall totals and wet days are negatively correlated (Figure 6a, 6c, Figure 7a) with the 'high summer' NAO index of Folland et al., (2009) and increased cyclonic activity (Figure 8a) as the Atlantic storm track is pushed further south than usual. Although daily rainfall extremes show similar seasonal patterns, only correlations in January, July, August and November are significant (Figure 6b). This implies that rainfall events and floods in some months may not have a direct relationship with the NAO, which in turn suggests that analysis of long-term NAO trends as a proxy for rainfall and flood frequency will only be valid for specific months of the year.

The NAO exerts its strongest influence over rainfall on Dartmoor during the summer, which corresponds with documentary evidence of several large summer floods associated with convective 'cloudbursts' and slow moving cyclonic storms during negative NAO phases in 1878, 1880, 1890, 1917 and 1930 (Table 4). During the last quarter of the 19th early 20th centuries, summer rainfall totals were above average in association with increased cyclonic activity in late 1870s, late 1880s/early 1890s, late 1900s/early-to-mid 1910s, 1920s and late 1930s (Figure 8a, Figure 9c). These periods of high rainfall correspond with negative NAO phases (Figure 7a) and an increased incidence of high daily rainfall totals (Figure 9d). There were also summer floods in 1784, 1826, 1840, 1844 and 1848, although there are no instrumental data covering these events. Given the influence of the SNAO on rainfall, these events will almost certainly have been related to slow moving thunderstorms and depressions when the jet stream was tracking further south than usual. Overall, the ratio of documented summer (JJA), autumn (SON) and winter (DJF) floods on Dartmoor (Table 4) is 7:3:2, respectively.

The period of high geomorphic activity from 1820-1930/1940s also covers some notable autumn and winter rainfall events associated with anomalous behaviour of the NAO. Following a decline from high annual rainfall in the 1870s/1880s, totals at Holne, Ashburton and Princetown began to rise after ca. 1900, peaking in the late 1920s and early 1930s (Figure 10) due to wetter autumn and winter periods (Figure 9e-9h). From 1910 to the mid-1920s there were a series of very wet autumn and winter periods on Dartmoor related to positive NAO values (Figure 7b, 7c) and increased cyclonic and southerly weather types (Figure 8b, 8c). As a result there was serious flooding in January 1927 and November 1929 (Table 4), as well as other notable autumnal floods in 1894 and 1944. These conditions are characteristic of upland areas of the UK where positive autumn/winter NAO anomalies result in prolonged frontal/orographically intensified rainfall over large areas (Figure 11) (Burt, 2005; Leaning and Brown, 2012). Rainfall of this type can occur at any time of the year, but is most common during the autumn (October-November) when sea surface temperatures are high and southwest winds dominant (Webb, 1987), associated with 'atmospheric rivers' of warm, moist air sourced from the subtropics (Lavers et al., 2011). High rates of berm sedimentation on Dartmoor in the early 20th century (Figure 5d) are probably a reflection of these conditions. Despite relatively few references concerning winter floods (Table 4), this does not mean they have not occurred on Dartmoor. Indeed, they may have been more frequent during the coldest phases of the Little Ice Age (Rumsby and Macklin, 1996), due to an increased probability of rain and thaw floods.

In terms of understanding the sharp decline in geomorphologically effective floods after ca. 1930/1940s in large catchments and ca. 1960-1970 in smaller systems (Figure 4, Figure 5), the rainfall record at Holne does not extend far enough into the 20th century to allow meaningful analysis. However, the Princetown record is more informative. Although there are uncertainties in linking daily rainfall totals to boulder-berm flood records, a marked change is evident after 1946 (Figure 12); before this date, daily falls approaching and over 100 mm were quite common, whereas after this date, with the exception of one notable event in the mid-1960s (which coincides with minor berm sedimentation), there was a marked decline, especially in the early 1950s, late 1960s and 1980 onwards.

Over the majority of the Dartmoor boulder-berm flood record, historical rainfall data show a good level of agreement, especially during the last quarter of the 19th century and early 20th century. However, the magnitude and frequency of geomorphologically effective floods began to decline at ca. 1930, whereas intense daily rainfall shows an increase (Figure 9d, 9f), as well as several documentary floods. These differences are probably due to (1): differences in short duration (extreme rainfall) totals that are not shown by daily values; (2) inability of documentary sources to describe flood magnitude, and (3): potential overestimation of berm age (Table 3). In the light of rainfall data the decline in geomorphic activity on Dartmoor may actually date to the mid-1940s, rather than ca. 1930. Of particular note is the marked reduction in heavy daily falls at Princetown after 1946.

DISCUSSION

The Dartmoor flood record: UK comparisons

Boulder-berm flood deposits have been dated in many upland areas of the UK (Macklin and Rumsby, 2007). The most comprehensive records are those for the North Pennines and Yorkshire Dales, with smaller data sets for the Brecon Beacons and Lake District. The only study of extreme floods that falls within the southwest precipitation variability area (Gregory et al., 1991) is that from the Brecon Beacons in south Wales (Macklin and Rumsby 2007). Two periods of increased upland flooding are evident in the Welsh record (Figure 13); the first between ca.1820 and ca.1870, with peaks in the ca.1850s and ca.1860s, and the second falling in the ca.1910s, with a smaller peak in the ca.1970s. These periods agree quite well with upland flooding on Dartmoor. A further aspect of similarity between the two records is that the largest dated flood on Dartmoor and in the Brecon Beacons occurred in the 19th century, which is different to northern England, where the largest dated floods occurred a century earlier (Macklin and Rumsby, 2007). The incidence of flooding in south Wales also declined sharply in the early 20th century, consistent with patterns in the southwest. These data point to regional patterns of flooding controlled by similar weather types and phases of the NAO. The declining magnitude of geomorphic activity on Dartmoor during the 20th century is also consistent with UK and European evidence of higher rates of flooding and sedimentation during earlier phases of the Little Ice Age (Merrett and Macklin, 1999; Gob et al., 2008).

Although there is evidence of a strong regional flood signal in the southwest precipitation variability area of the UK, data from northern England also show a degree of similarity with Dartmoor. Johnson and Warburton (2002) dated boulder – berm flood units in the Lake District to ca.1844-1859, ca.1860-1880, ca.1891-1901, ca.1911-1919 and ca.1929-1935, whilst Watkins and Whyte's (2008) documentary series identified flood peaks in the last quarter of the 19th century and first half of the 20th century. Data from the North Pennines and Yorkshire Dales also show similarities with the Dartmoor record, with increased flood activity from ca.1850 to ca.1880 (Figure 13), which appears to have been a period of severe flooding in many upland British catchments. The peak frequency of berm deposition on Dartmoor in the early 20th century also corresponds with a marked increase in flooding in the North Pennines. Although the frequency of geomorphologically effective floods in the British uplands may have peaked in the 20th century, sedimentary records from northern England are very similar to Dartmoor in that both regions show a marked reduction in flood magnitude during the 20th century. In the Yorkshire Dales, flood magnitude declined sharply after ca. 1900, despite flood frequency remaining at relatively high levels (Merrett and Macklin, 1999), whilst in the North Pennines a general decline in flood competence began in the late ca.1700s, a trend that was especially marked after ca.1950 (Macklin et al., 1992).

Differences in the timing of upland flooding in the UK can be explained, to a large extent, by variability in the NAO and the position and organisation of summer storm cells and autumn and winter storm tracks. Local factors, such as snow water equivalent and rate of melt during rain and thaw events (Macdonald, 2012) will also be important. There may also be differences in flood seasonality between the southwest and north of England. Although there may be little difference in likelihood of summer/autumn storms in the British uplands, thaw related floods on Dartmoor have certainly been uncommon historically, whereas these types of event have been (and are) more significant in northern England and Scotland (Rumsby and Macklin, 1994; Merrett and Macklin, 1999; Macdonald, 2012; McEwen, 2006), often producing some of the most extreme flows. The mean January temperature (1981-2010) on Dartmoor is typically 3-4^{o}C, compared to 0-2^{o}C across the hills of northern England (Mayes and Wheeler, 2013). These temperature differences mean that snowfall and subsequent melt events are more likely in the latter areas, especially when cold snaps associated with negative winter NAO conditions terminate abruptly with rapid melting and persistent rainfall.

Whilst geomorphological flood records from small upland catchments show a certain degree of similarity across the UK, they differ from long-instrumental series augmented with historical data from lowland areas of large/very large catchments (>1 x 10^3 km^2) (e.g. Yorkshire Ouse at York (Macdonald, 2012), River Eden at Sheepmount (Pattison and Lane, 2012), River Tay (McEwen, 2006)).

Geomorphological flood records, including Dartmoor, show historically low levels of activity in small upland catchments from the 1980s to 2000 (Rumsby and Macklin, 2007), whereas long instrumental/historical flow records, (e.g. Ouse at York and Eden at Sheepmount), are either flood-rich or show clustering over the same period. These differences are partly due to land-use impacts associated with lowland drainage and agricultural intensification (Longfield and Macklin, 1999), but also differences in the scale of flood generating meteorological conditions in catchments of different size. Small upland catchments (< 25 km^2) tend to be most severely affected by isolated convective storms (Carling, 1986), but these events tend to affect only a fraction of much larger drainage systems. Indeed, Macdonald (2012) noted that flash floods in small upland catchments of the Yorkshire Ouse (Merrett and Macklin, 1999) rarely, if ever, generate sufficient volume to affect distant lowland areas (e.g. York) as flows attenuate. Due to these scale effects it is likely that lowland gauged records from large/very large catchments do not adequately record small convective storms in the distant uplands (because only a small percentage of the larger catchment area is contributing runoff). The late 20th century decline in geomorphically effective floods in the British uplands corresponds very closely with a decrease in heavy upland summer rainfall (Burt and Ferranti, 2012), related to anomalous behaviour of the SNAO in its positive mode, which typically correlates with drier, warmer and sunnier than average conditions in northwest Europe, from 1965-2005 (Figure 14). The period 1965-2005 was the most consistently positive in the whole SNAO record back to 1850, as well as the reconstructed series back to 1700 (Linderholm et al., 2008). These patterns agree with periods of less frequent extreme floods on Dartmoor and the British uplands, and confirm that the SNAO is a very important control on summer heat, drought, and flooding in northwest Europe (Folland et al., 2009).

In contrast, the most extreme floods in lowland areas of large/very large catchments tend to be associated with regional-scale, long duration frontal rainfall, which saturates entire river catchments (e.g autumn 2000, 2012; McEwen, 2006). This means that all tributaries and sub-catchments experience high flows, producing severe floods at the most downstream sites, such as the Ouse at York, where flood seasonality is dominated by autumn and winter events (Macdonald, 2012). There is a significant difference in the hydrology of this type of long duration rainfall event compared to a summer thunderstorm. The former are associated with rainfall totals of >80-100 mm accumulating over 1-2 days and falling over an entire catchment, whereas convective summer storms and flash floods are associated with localised rainfall totals of >150-200 mm in 3-6 hours. Regional-scale autumn/winter rainfall events have increased in many areas of the UK over recent decades (Osborn and Hulme, 2002; Jones et al., 2012a) corresponding with flood-rich episodes in large systems, whilst at the same time mirrored by declining heavy summer rainfall and extreme floods in the uplands (pre-2007). This is an important finding as it suggests that different areas of the same drainage basin (uplands and lowlands) may have different flood seasonality and flood records, and will respond differently to future climatic change.

Boulder-berm records and implications for flood risk management on Dartmoor

The importance of utilizing geomorphological data to understand flood risk can be assessed by comparing gauged flow and boulder berm records. Figure 15 shows the boulder-berm record for the River West Okement (see Figure 1 for location) directly upstream from a local gauging station, which opened in 1968. It is evident from these data that: (1) no extreme floods have occurred on this river since the early 20th century (the last documented event was August 1917) and (2); peak frequency of the largest floods occurred in the mid-19th century. Recent flows are very likely, therefore, to have been of lower magnitude than 19th century events (although boulders could have been entrained and moved along the channel bed). Figure 16 shows specific discharges of the largest gauged flows on Dartmoor compared to other large regional events. The only flood of note occurred on the River Dart at Austins Bridge in 1979 (Table 4), which plots just above the normal maximum flood. However, the drainage area at Austins bridge is >200 km^2 and discharges for the same event in smaller headwater catchments (20-50 km^2) plot well below the normal maximum flood. This is typical of many short gauge records in the UK that do not cover two very wet periods in the UK: the last quarter of the 19th century and first quarter/half of the 20th century. Although palaeoflood data are not used in the UK to inform flood risk, such methodologies are common in the US, especially when considering dam safety (Baker, 2008), and they have obvious benefits for extending the flood series of small upland river systems in the UK.

CONCLUSIONS

The key aim of this research was to elucidate magnitude-frequency relationships of extreme floods in the southwest uplands. This paper shows that extreme flood events in small upland catchments show marked temporal variability, which is controlled, to a large extent, by sub-decadal variability of the NAO and its effect on precipitation. Since ca. 2007 it would appear that the magnitude and frequency of upland flooding has increased in some parts of the UK, with a recent event in the North Pennines of similar magnitude to historical floods (Milan, 2012), as well as a series of large floods elsewhere. Following at least one, possibly two decades (1990-2010) without boulder-berm deposition, extreme flooding on Dartmoor is currently at historically low levels, primarily due to a decrease in heavy rainfall events. Any increase to peak levels recorded in the mid-to-late 19th century and early 20th century may pose significant flood risk to upland communities in the southwest, especially in locations where floodplains have been developed, impounded, or where river valley floors form a focal point of recreational activity (e.g. campsites). Dartmoor has the potential to generate very large and damaging floods and probable maximum precipitation in the area is ca. 450 mm (Clark, 1995). The potential for catastrophic consequences is well illustrated by a flash flood on the River Plym in 1970 (Table 4) and events in Cumbria during autumn 2009 associated with 316 mm of rainfall in 24 hours. This research highlights the importance of geomorphological data to extend flood records, particularly where the largest floods are significantly older than gauged data. The dangers of not accounting for historical flood frequency and magnitude may lead to an underestimate of flood risk.

ACKNOWLEDGEMENTS

We would especially like to thank Barbara Benfield (British Lichen Society) for her time helping to identify lichen species on Dartmoor. Professor Chris Folland (Met Office) kindly supplied his summer NAO data. We would also like to thank Richard

Horsham and Dr. Susan Andrew (Plymouth University) for their comments concerning documentary flood events, and Sarah Foulds for her assistance in the field. The comments of two anonymous reviewers helped to improve this manuscript. Finally, we owe retrospective thanks to the late 19th and early 20th century meteorologists of Dartmoor who kept meticulous rainfall records for the benefit of future generations. Specifically, Reverend John Gill, Rector of Holne (1858-1917), Mr L. Frost (Holne, 1917-1945) and the Amery family who kept the rainfall record at Druid, Ashburton, from 1866 to1928. We are also indebted to RH Worth (1868-1950) for his numerous accounts of severe weather and flooding on Dartmoor. This research project was supported by HEFCW (Higher Education Funding Council for Wales) through the Centre for Catchment and Coastal Research, Aberystwyth University.

References

Acreman, MC. 1989. Extreme historical UK floods and maximum flood estimation. *Journal of the Institute of Water Environment. Management* **3**: 404-412.

Acreman, MC. 1991. The flood of July 25th 1983 on the Hermitage Water, Roxburghshire. *Scottish Geographical Magazine* **107**: 170-178.

Armstrong R, Bradwell T. 2010. Growth of crustose lichens: a review. *Geografiska Annaler: Series A* **92**: 3-17.

Baker VR. 2008. Paleoflood hydrology: Origin, progress, prospects. *Geomorphology* **101**: 1-13.

Ballantyne CK, Harris C. 1994. *The Periglaciation of Great Britain*. Cambridge University Press, Cambridge.

Barredo JI. 2007. Major flood disasters in Europe: 1950–2005. *Natural Hazards* **42**: 125-148.

Beer KE, Scrivener RC. 1982. Metalliferous mineralisation. In *The Geology of Devon*, Durrance EM, Laming DJC (eds). University of Exeter: Exeter; 117 - 147.

Bradwell T. 2009. Lichenometric dating: a commentary in light of some recent statistical analysis. *Geografiska Annaler: Series A* **91**: 61-69.

Burnard R. 1896. Dart floods. *Reports and Transactions of the Devonshire Association* **28**: 60-61.

Burnard R. 1901. The great flood of February 15th 1900. *Reports and Transactions of the Devonshire Association*: **33**, 99.

Burt S. 2005. Cloudburst upon Hendraburnick Down: The Boscastle Storm of 16th August 2004. *Weather* **60**, 219-227.

Burt T, Holden J. 2010. Changing temperature and rainfall gradients in the British uplands. *Climate Research* **45**: 57-70.

Burt T, Ferranti EJS. 2012. Changing patterns of heavy rainfall in upland areas: a case study from northern England. *International Journal of Climatology* **32**: 518-532.

Cargill A, MacConnachie AM, Perrett JC. 2004. Flash flood on the Craigie Burn, Perth, Scotland. *Weather* **59**: 12-14.

Carling PA. 1986. The Noon Hill flash floods: July 17th 1983. Hydrological and geomorphological aspects of a major formative event in an upland landscape. *Transactions of the Institute of British Geographers* **11**: 105-118.

Cenderelli DA, Cluer BL. 1998. Depositional processes and sediment supply in resistant-boundary channels: examples from two case studies. In *Rivers Over Rock: Fluvial Processes in Bedrock Channels*, Tinkler KJ, Wohl EE (eds). Geophysical Monograph Series 107. American Geophysical Union: Washington; 105-132.

Chen Y, Clark AH, Farrar E, Wasteneys HAHP, Hodgson MJ, Bronley MV. 1993. Diachronous and independent histories of plutonism and mineralization in the Cornubian Batholith, southwest England. *Journal of the Geological Society* **150**: 1183-1191.

Clark C. 1995. New estimates of probable maximum precipitation in South West England. *Meteorological Applications* **2**: 307-312.

Cornwall Council. 2011. *Preliminary Flood Risk Assessment. Annex 5: Chronology of Major Flood Events in Cornwall* (http://publications.environment-agency.gov.uk/PDF/FLHO1211BVMH-E-E.pdf). Accessed 18/05/12.

Costa JE. 1983. Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. *Geological Society of America Bulletin* **94**: 986-1004.

Coxon P, Coxon CE, Thorn RH. 1989. The Yellow River (County Leitrim, Ireland) flash flood of June 1986. In *Floods: Hydrological, Sedimentological and Geomorphological Implications,* Beven K, Carling P (eds). Wiley: Chichester; 199-217.

Crossing. W. 1888. *Amid Devonia's Alps: Wanderings and Adventures on Dartmoor*. WH Luke: Plymouth.

Crossing W. 1901. *100 Years on Dartmoor: Historical Notices on the Forest and its Purlieus During the Nineteenth Century*. Western Morning News: Plymouth.

Delrieu G, Ducrocq V, Gaume E, Nicol J, Payrastre O, Yates E, Kirstetter PE, Andrieu H, Ayral PA, Bouvier C, Creutin JD, Livet M, Anquetin A, Lang M, Neppel L, Obled C, Parent-Du-Chatelet J, Saulnier GM, Walpersdorf A, Wobrock W. 2005. The catastrophic flash-flood event of 8–9 September 2002 in the Gard Region, France: a first case study for the Cévennes–Vivarais Mediterranean Hydrometeorological Observatory. *Journal of Hydrometeorology* **6**: 34-52.

Dobie CH, Wolf PO. 1953. The Lynmouth flood of August 1952. *Proceedings of the Institute of Civil Engineers* **2**: 522-588.

Evans DJA, Harrison S, Viel A, Anderson E. 2012. The glaciation of Dartmoor: the southernmost independent Pleistocene ice cap in the British Isles. *Quaternary Science Reviews* **45**: 31-53.

Folland CK, Knight J, Linderholm HW, Fereday D, Ineson S, Hurrell J. 2009. The summer North Atlantic Oscillation: past, present, and future. *Journal of Climate* **22**: 1082-1103.

Foulds SA, Brewer PA, Macklin MG, Betson R, Rassner, SME. 2012. *Causes and consequences of a large summer storm and flood in west Wales, 8th-9th June 2012*. Fluvio consultancy report 2012/01/73, 53 pp.

Gaume E, Livet M, Desbordes M, Villeneuve J.-P. 2004. Hydrological analysis of the River Aude, France, flash flood on 12 and 13 November 1999. *Journal of Hydrology* **286**: 135-154.

Gaume E, Bain V,Bernardar P, Newinger O, Barbuc M, Bateman A, Blaskovicova L, Loschl G, Borga M, Dumitrescu A, Daliakopoulos I, Garcia J, Irimescu A, Kohnova S, Marchi L, Matreata S, Medina V, Preciso E, Sempere-Torres D, Stancalie G, Szolgay J, Tsanis I, Velasco D, Viglione A. 2009. A compilation of data on European flash floods. *Journal of Hydrology* **367**: 70-78.

Gob F, Petit F, Bravard J-P, Ozera A, Gob A. 2003. Lichenometric application to historical and sub recent dynamics and sediment transport of a Corsican stream (Figarella River – France). *Quaternary Science Reviews* **22**: 2111-2124.

Gob F, Jacob N, Bravard J-P, Petit F. 2008. The value of lichenometry and historical archives in assessing the incision of submediterranean rivers from the Little Ice Age in the Ardeche and upper Loire (France). *Geomorphology* **94**: 170-183.

Gob F, Bravard J-P, Petit F. 2010. The influence of sediment size, relative grain size and channel slope on initiation of sediment motion in boulder bed rivers. A lichenometric study. *Earth Surface Processes and Landforms* **32**: 1535-1547.

Greeves T, Stanbrook E. 2004. *The Clapper Bridge – Postbridge*. Quay: Brixham.

Gregory JM, Jones PD, Wigley TML. 1991. Precipitation in Britain: an analysis of area averaged data updated to 1989. *International Journal of Climatology* **11**: 331-345.

Gutiérrez F, Gutiérez M, Sancho C. 1998. Geomorphological and sedimentological analysis of a catastrophic flash flood in the Arfis drainage basin (Central Pyrenees, Spain). *Geomorphology* **22**: 265-283.

Hand WH, Fox NI, Collier CG. 2004. A study of twentieth-century extreme rainfall events in the United Kingdom with implications for forecasting. *Meteorological Applications* **11**: 15-31.

Hannaford J, Marsh TJ. 2008. High-flow and flood trends in a network of undisturbed catchments in the UK. *International Journal of Climatology* **28**: 1325-1338.

Hemery E. 1978. *High Dartmoor: Land and People*. Robert Hale: London.

Horsham R. 2012a. Understanding the Dartmoor landscape part 5: summer floods on Dartmoor. *Dartmoor* **106**: 30-32.

Horsham R. 2012b. Record of summer thunderstorms and floods on Dartmoor. *Dartmoor* **108**: 56.

Huntingdon TG. 2006. Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology* **319**: 83-95.

Hurrell JW. 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* **269**: 676-679.

Johnson RM, Warburton J. 2002. Flooding and geomorphic impacts in a mountain torrent: Raise Beck, central Lake District, England. *Earth Surface Processes and Landforms* **27**: 945-969.

Jones MR, Fowler HJ, Kilsby CG, Blenkinsop S. 2012a. An assessment of changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009. *International Journal of Climatology*. DOI:10.1002/joc.3503

Jones PD, Harpham C, Briffa KR. 2012b. Lamb weather types derived from reanalysis products. *International Journal of Climatology.* DOI: 10.1002/joc.3498.

Lavers DA, Allan RP, Wood EF, Villarini G, Baryshaw DJ, Wade AJ. 2011. Winter floods in Britain are connected to atmospheric rivers. *Geophysical Research Letters* **38**, L23803: 1-8.

Leaning HW, Browning KA. 2012. Quantification of the importance of wind drift to the surface distribution of orographic rain on the occasion of the extreme Cockermouth flood in Cumbria. *Quarterly Journal of the Royal Meteorological Society*. DOI:10.1.1002/qj.2024.

Lenzi MA, Mao L, Comiti F. 2006. When does bedload transport begin in steep boulder-bed streams? *Hydrological Processes* **20**: 3517-3533.

Lewin J, Macklin MG. 2003. Preservation potential for Late Quaternary river alluvium. *Journal of Quaternary Science* **18**: 107-120.

Lewin J, Macklin MG. 2010. Floodplain catastrophes in the UK Holocene: messages for managing climate change. *Journal of Hydrology* 24: 2900-2911.

Linderholm HW, Folland CK, Hurrell JW. 2008. Reconstructing summer North Atlantic Oscillation (SNAO) variability over the last five centuries. In *TRACE - Tree Rings in Archaeology, Climatology and Ecolog,* Elferts D, Brumelis G, Gärtner H, Helle G, Schleser G (eds.). Proceedings of the DENDROSYMPOSIUM 2007. Scientific Technical Report 08/05, *Vol. 6*: Potsdam; 6 - 13.

Longfield SA, Macklin MG. 1999. The influence of recent environmental change on flooding and sediment fluxes in the Yorkshire Ouse basin. *Hydrological Processes* **13**: 1051-1066.

Maas GS, Macklin MG, Warburton J, Woodward JC, Meldrum, EA. 2001. 300-year history of flooding in Andean mountain river system: the Rio Alizos, southern Bolivia. In *River Basin Sediment Systems: Archives of Environmental Change*, Maddy D, Macklin MG, Woodward JC (eds.). Balkema: Rotterdam; 297-323.

Maas GS, Macklin MG. 2002. The impact of recent climate change on flooding and sediment supply within a Mediterranean mountain catchment, southwestern Crete, Greece. *Earth Surface Processes and Landforms* **27**: 1087-1105.

Macklin MG. 1997. Fluvial geomorphology of north-east England. In *Fluvial Geomorphology of Great Britain*, Gregory KJ (ed). Chapman Hall: London; 203-238.

Macklin MG, Rumsby BT. 2007. Changing climate and extreme floods in the British uplands. *Transactions of the Institute of British Geographers* **32**: 168-186.

Macklin MG, Rumsby BT, Heap T. 1992. Flood alluviation and entrenchment: Holocene valley floor development and transformation in the British uplands. *Geological Society of America Bulletin* **104**: 631-643.

Macdonald N. 2012. Trends in flood seasonality of the River Ouse (northern England) from archive and instrumental sources since AD 1600. *Climatic Change* **110**: 901-923.

Macdonald N, Black AR. 2010. Reassessment of flood frequency using historical information for the River Ouse, York, UK. *Hydrological Sciences Journal* **7**: 1152-1162.

Manning-Saunders R. 1951. The River Dart. Westaway Books: London.

Marchi L, Borga M, Preciso E, Gaume E. 2010. Characterisation of selected extreme flash floods in Europe and implications for flood risk management. Hydrological Processes 394: 118-133.

Mason PJ, Hinks JL, 2008. Security of stepped masonry spillways: lessons from Ulley dam. Dams and Reservoirs 18: 5-8.

Mayes J, Wheeler D. 2013. Regional weather and climates of the British Isles - Part 1: Introduction. Weather 68: 3-8.

McEwen LJ. 2006. Flood seasonality and generating conditions in the Tay catchment, Scotland from 1200 to present. *Area* **38**: 47-64.

Merrett SP, Macklin MG. 1999. Historic river response to extreme flooding in the Yorkshire Dales, northern England. In *Fluvial Processes and Environmental Change*, Brown AG, Quine TM (eds). Wiley: Chichester; 345-360.

Milan D. 2012. Geomorphic impact and system recovery following an extreme flood in an upland stream: Thinhope Burn, northern England, UK. *Geomorphology* **138**: 319-328.

Norbiato D, Borga M, Sangati M, Zanon F. 2007. Regional frequency analysis of extreme precipitation in the eastern Italian Alps and the August 29, 2003 flash flood. *Journal of Hydrology* **345**: 149-166.

Osborn TJ. 2006. Recent variations in the winter North Atlantic Oscillation. *Weather* **61**: 353-355.

Osborn TJ, Hulme M. 2002. Evidence for trends in heavy rainfall events over the UK. *Philosophical Transactions of the Royal Society of London: Series A* **360**: 1313-1325.

Pall P, Aina T, Stone DA, Scott PA, Nozawa T, Hilberts AGJ, Lohmann D, Allen MR. 2011. Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature* **470**: 382-386.

Pattison I, Lane SN. 2012. The relationship between Lamb weather types and long-term changes in flood frequency, River Eden, UK. *International Journal of Climatology* **32**: 1971-1981.

Robson AT. 2002. Evidence for trends in UK flooding. *Philosophical Transactions of the Royal society of London A* **360**: 1327-1343.

Roca M, Davison M. 2009. Two dimensional model analysis of flash-flood processes: application to the Boscastle event. *Journal of Flood Risk Management* **3**: 63-71.

Rodda, HJE, Little MA, Wood RG, MacDougall, McSharry PE. 2009. A digital archive of extreme rainfalls in the British Isles from 1866 to 1968 based on *British Rainfall*. *Weather* **64**: 71-75.

Rumsby BT, Macklin MG. 1994. Channel and floodplain response to recent abrupt climate change: The Tyne basin, northern England. *Earth Surface Processes and Landforms* **19**: 499-515.

Rumsby BT, Macklin MG. 1996. River response to the last Neoglacial cycle (the 'Little Ice Age') in northern, western and central Europe. In *Global Continental Changes: The Context of Palaeohydrology*, Branson J, Brown AG, Gregory KJ (eds). Geological Society Special Publication: London **115**: 217–233.

Stanbrook E. 1994. *Dartmoor Forest Farms: A Social History from Enclosure to Abandonment*. Halsgrove: Wellington.

Thorndycraft VR, Pirrie D, Brown AG. 2004. Alluvial records of medieval and prehistoric tin mining on Dartmoor, southwest England. *Geoarchaeology* **19**: 219-236.

Walker JP. 2008. The discontinuance of Boltby reservoir, North Yorkshire, UK. *Dams and Reservoirs* **18**: 17-21.

Watkins S, Whyte I. 2008. Extreme flood events in upland catchments in Cumbria since 1600: the evidence of historical records. *North West Geography* **8**: 33-41.

Webb JDC. 1987. Britain's highest daily rainfalls: the county and monthly records. *Journal of Meteorology* **12**: 263-266.

Wohl E. 1992. Bedrock benches and boulder bars: floods in the Burdekin Gorge of Australia. *Geological Society of America Bulletin* **104**: 770-778.

Worth RH. 1918. Thirty-sixth report (3rd series) of the committee on the climate of Devon: The thunderstorm of August 14th. *Reports and Transactions of the Devonshire Association* **50**: 234-242.

Worth RH. 1924. Forty-second report (3rd series) of the committee on the climate of Devon. *Reports and Transactions of the Devonshire Association* **56**: 153-169.

Worth RH. 1930. Forty-eight report (3rd series) of the committee on the climate of Devon. *Reports and Transactions of the Devonshire Association* **62**: 135-152.

Worth RH. 1931. Forty-eight report (3rd series) of the committee on the climate of Devon. *Reports and Transactions of the Devonshire Association* **63**: 105-121.

Worth RH. 1939. Fifty-seventh report (3rd series) of the committee on the climate of Devon. *Reports and Transactions of the Devonshire Association* **71**: 91-108.

Worth RH. 1945. Sixty-third report (3rd series) of the committee on the climate of Devon. *Reports and Transactions of the Devonshire Association* **77**: 69-86.

Worth RH. 1971. *Worth's Dartmoor: compiled from the published works of the late R. Hansford Worth*. David & Charles: Newton Abbott.

Figure 1. Dartmoor, showing study catchments and the location of graveyards and other dating control surfaces in the uplands. Some of the smaller catchments are labelled 1-6.

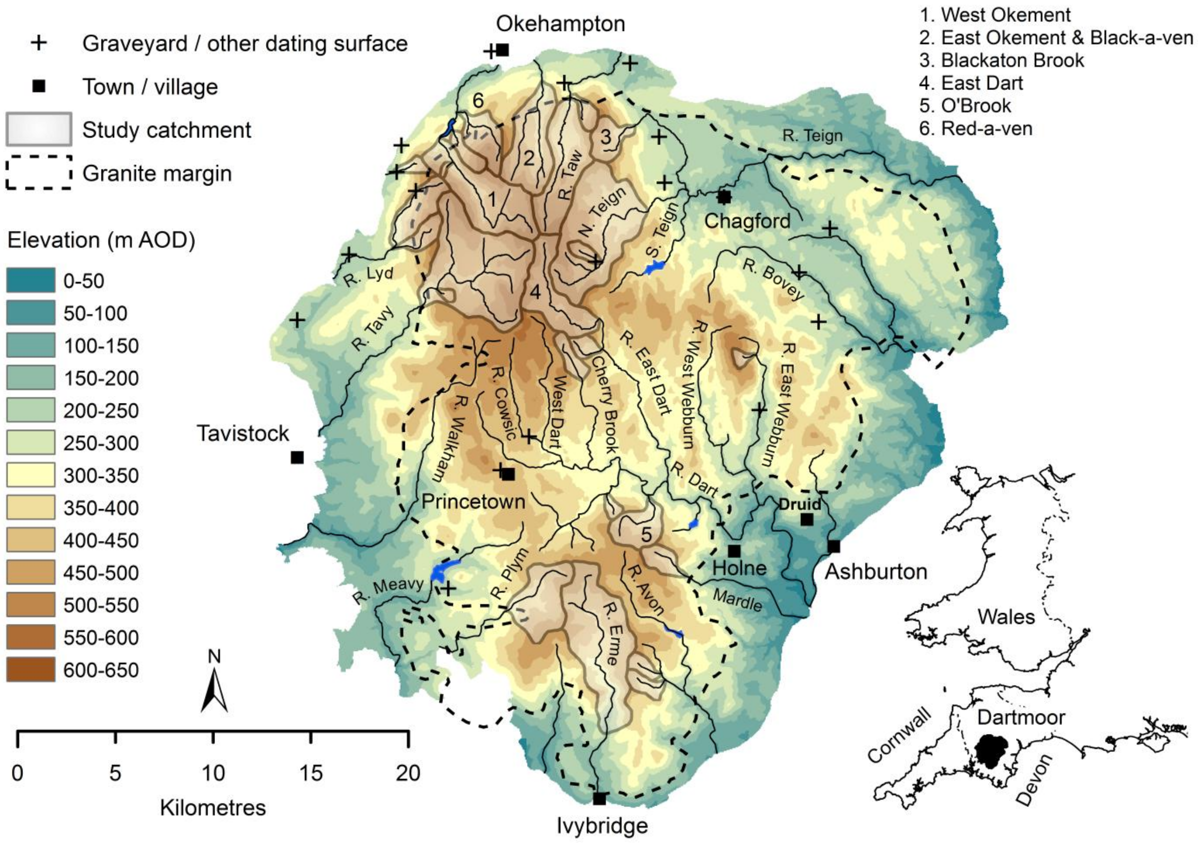

Figure 2. Age-size relationships of lichen species used in this study. Lichens were identified with the assistance of a regional expert from the British Lichen Society.

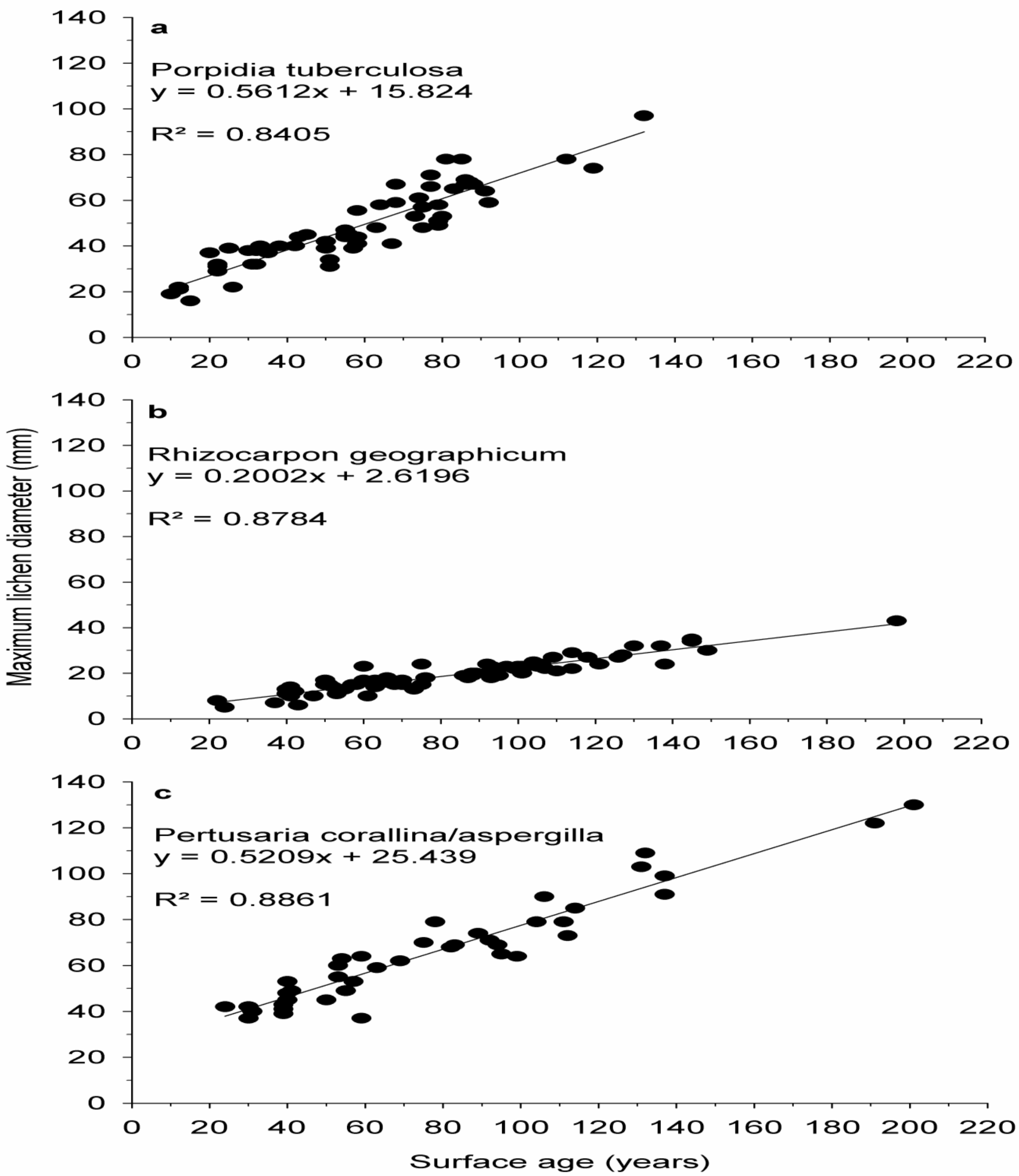

Figure 3. Proximal section of a boulder-berm deposited in a bedrock section of Red-a-ven Brook, northern Dartmoor. Based on the largest *Porpidia tuberculosa* (74 mm) and *Rhizocarpon geographicum* (22 mm) specimens this berm dates to 1907-1914 and corresponds very well with a documented flood in 1917 that was described at this precise location by Worth (1918). A second berm on a tributary of Red-a-ven Brook (Sniper's Gully) that was generated by the same flood and photographed shortly after the event (shown in Worth's, 1971 compilation) was dated to 1928 using *Pertusaria species*.

Figure 4. Boulder-berm flood magnitude plots for small (<1.5 km^2; 4a, 4b), medium ($\geq$1.5 <10 km^2; 4c, 4d) and large ($\geq$10 km^2; 4e, 4f) catchments based on maximum and mean (3 largest clasts) b-axis data. Both measures of magnitude have been used because the degree of imbrication at some sites meant that accurate measurement of three boulders was not possible. For berms less than 120 years in age, error bars show one standard deviation. Because there is a trend of decreasing dating accuracy with increasing lichen size, berms older than the range of our validated data (ca. 120 years (Table 3)) show two standard deviations.

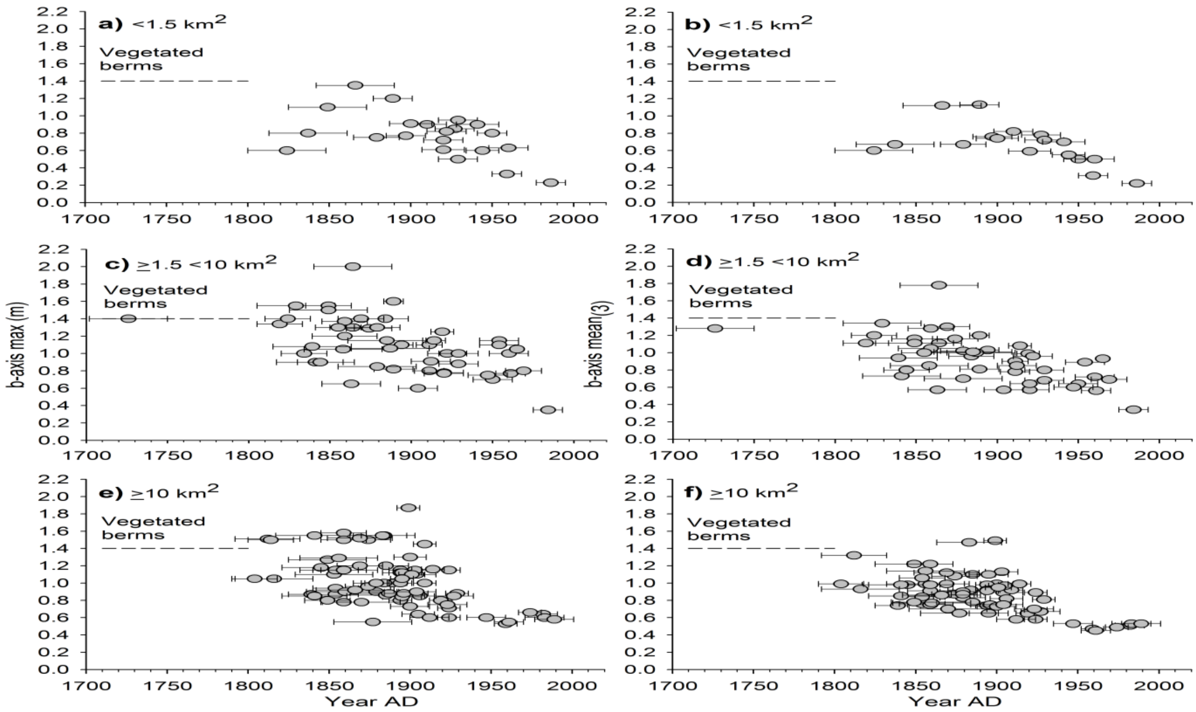

Figure 5. Summary decadal frequency of boulder-berm sedimentation for (a) small, (b) medium, and (c) large catchments. Figures 5d and 5e show aggregated data and the number of documented floods. Hatching on 5e represents uncertainty associated with the 1956/1965 flood. The timing of decadal peaks must be considered in conjunction with error bars and error estimates shown in Table 3.

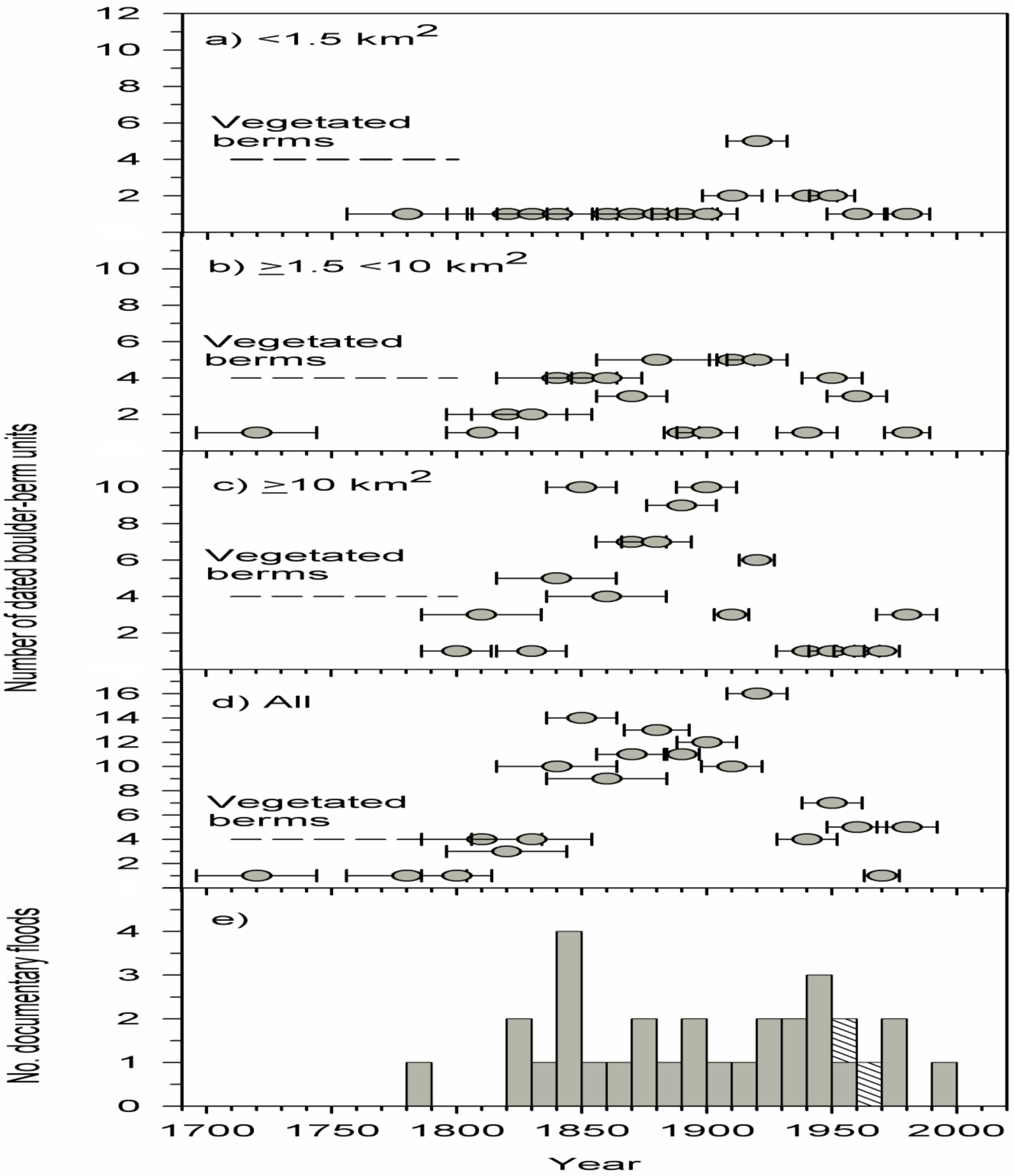

Figure 6. Correlation of rainfall data at Holne vicarage (1876-1917) and Holne (1917-1945), southeast Dartmoor (see Figure 1 for location) with NAO index values for (a) total monthly rainfall, (b) daily maximum rainfall and (c) number of wet days (≥0.25 mm). Statistical significance is shown where p <0.05. The original record at Holne vicarage ended in 1917 when the rain gauge was moved ca. 0.5 km away to Holne village (9 m lower in altitude) and ran until 1945.

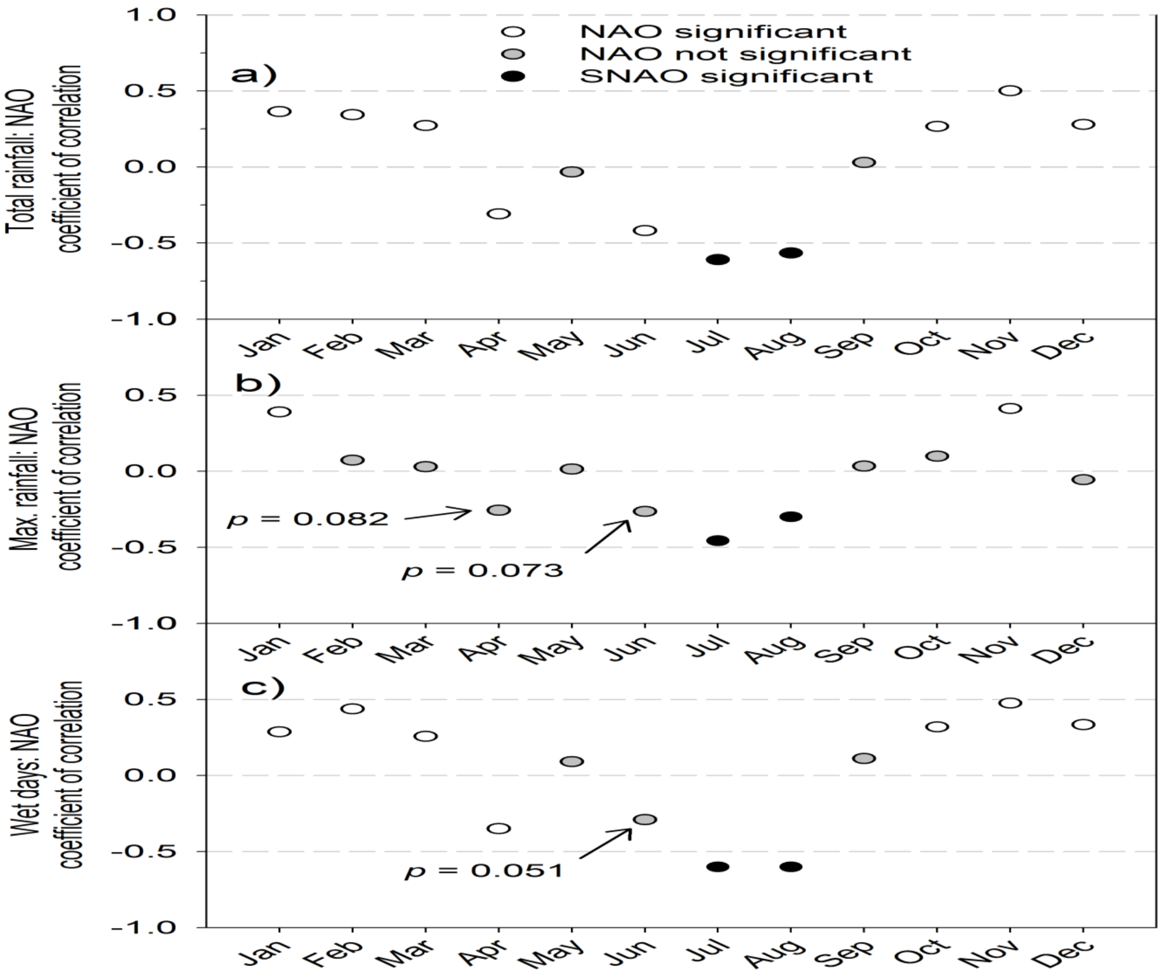

Figure 7. The strongest seasonal Holne rainfall: NAO relationships (monthly totals) as shown in Figure 6.

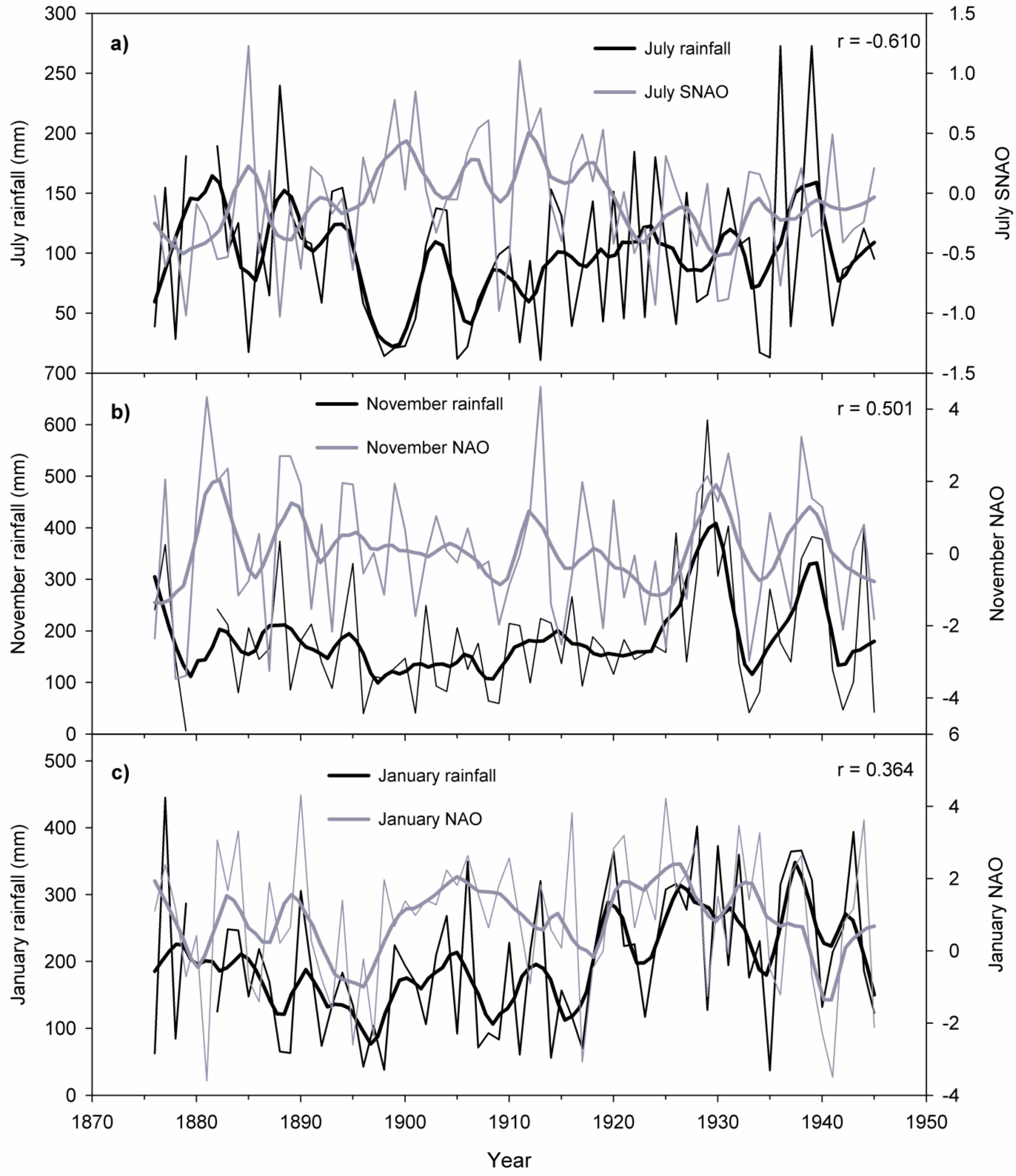

Figure 8. Time series of seasonal rainfall at Holne plotted alongside Lamb Weather Types (LWTs). Coefficients of correlation are shown in the top right hand corner (p< 0.05). Period means (1876-1945) from which anomalies have been calculated are 213.1 mm (Jul-Aug), 358.3 mm (Oct-Nov) and 694.8 (Dec-Mar). LWTs are based on Jones et al., (2012b).

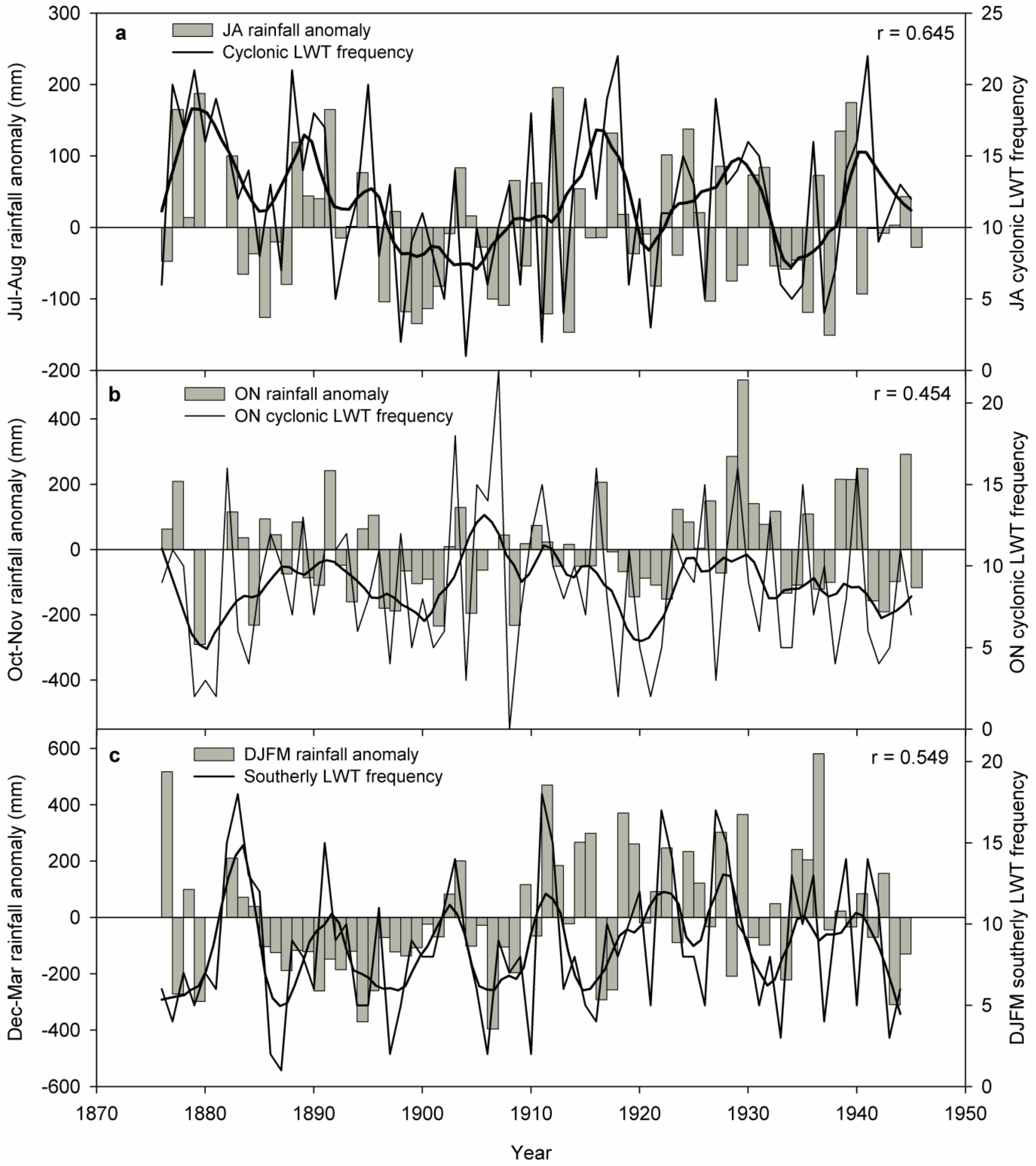

Figure 9. Seasonal rainfall totals and maximum daily rainfall at Holne (1876-1945).

The dashed line indicates the change of gauge location.

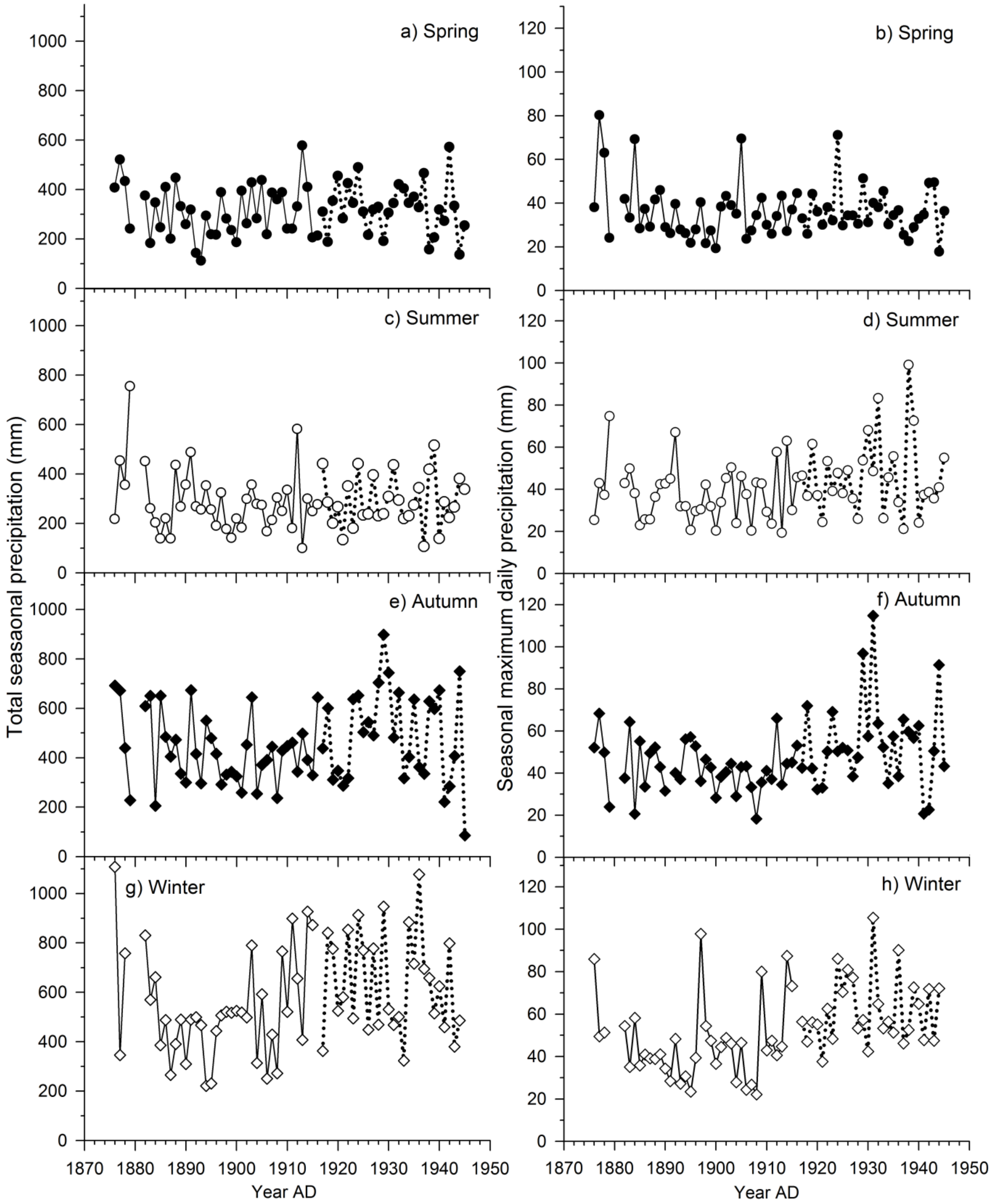

Figure 10. Annual precipitation at Holne, Ashburton and Princetown. Note that the shorter Holne record is plotted on a different x-axis scale.

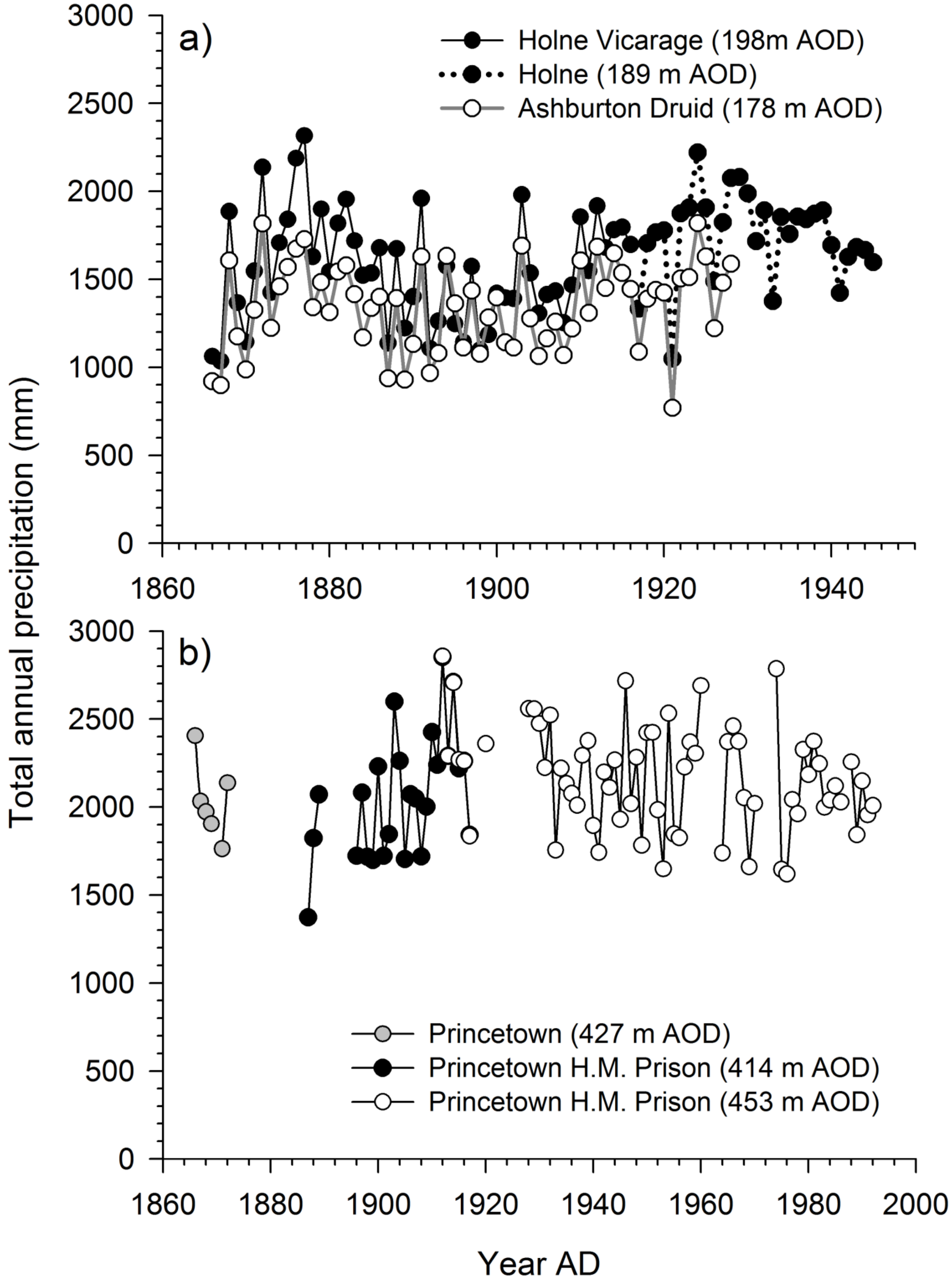

Figure 11. Rainfall totals and NAO data based on Hand et al., (2004) and updated with data from Boscastle 2004, Cumbria 2009 and west Wales 2012.

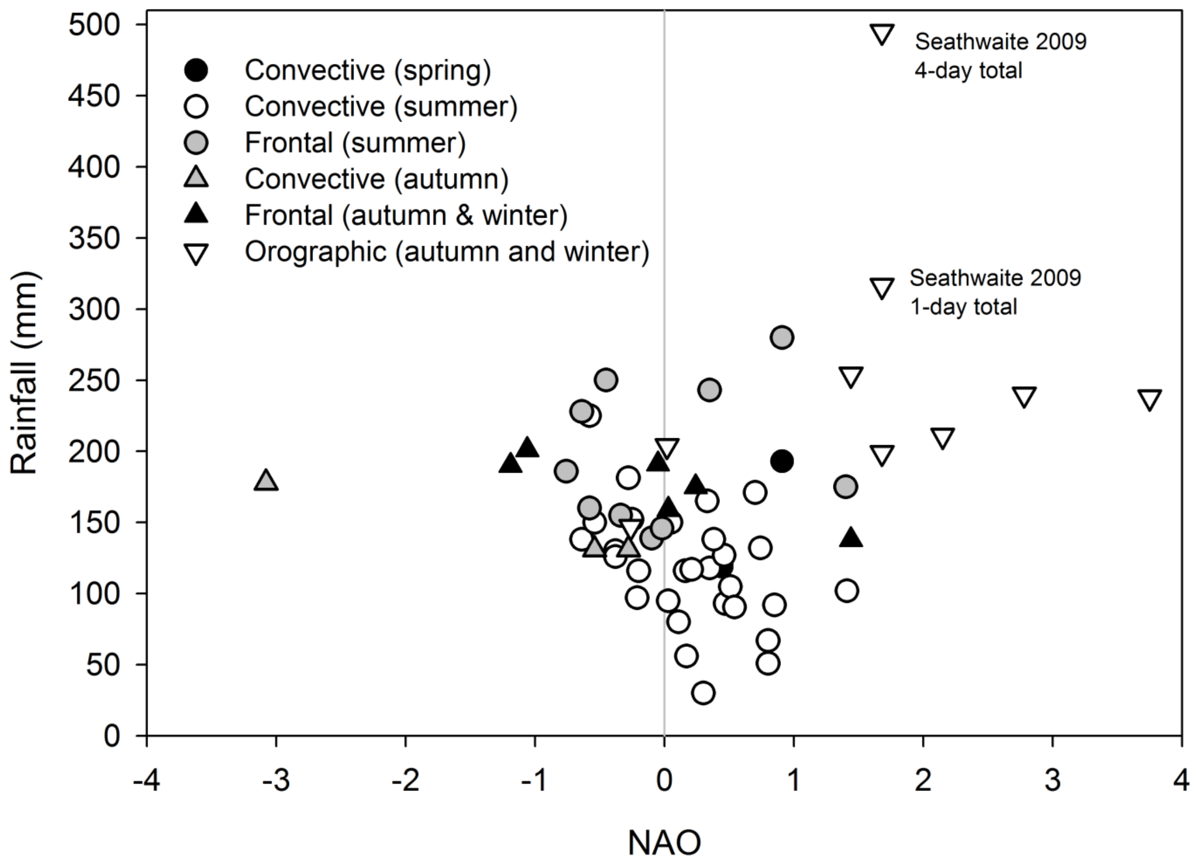

Figure 12. Maximum daily rainfall totals at various rain gauges that have operated at Princetown, central Dartmoor, since the late 19th century.

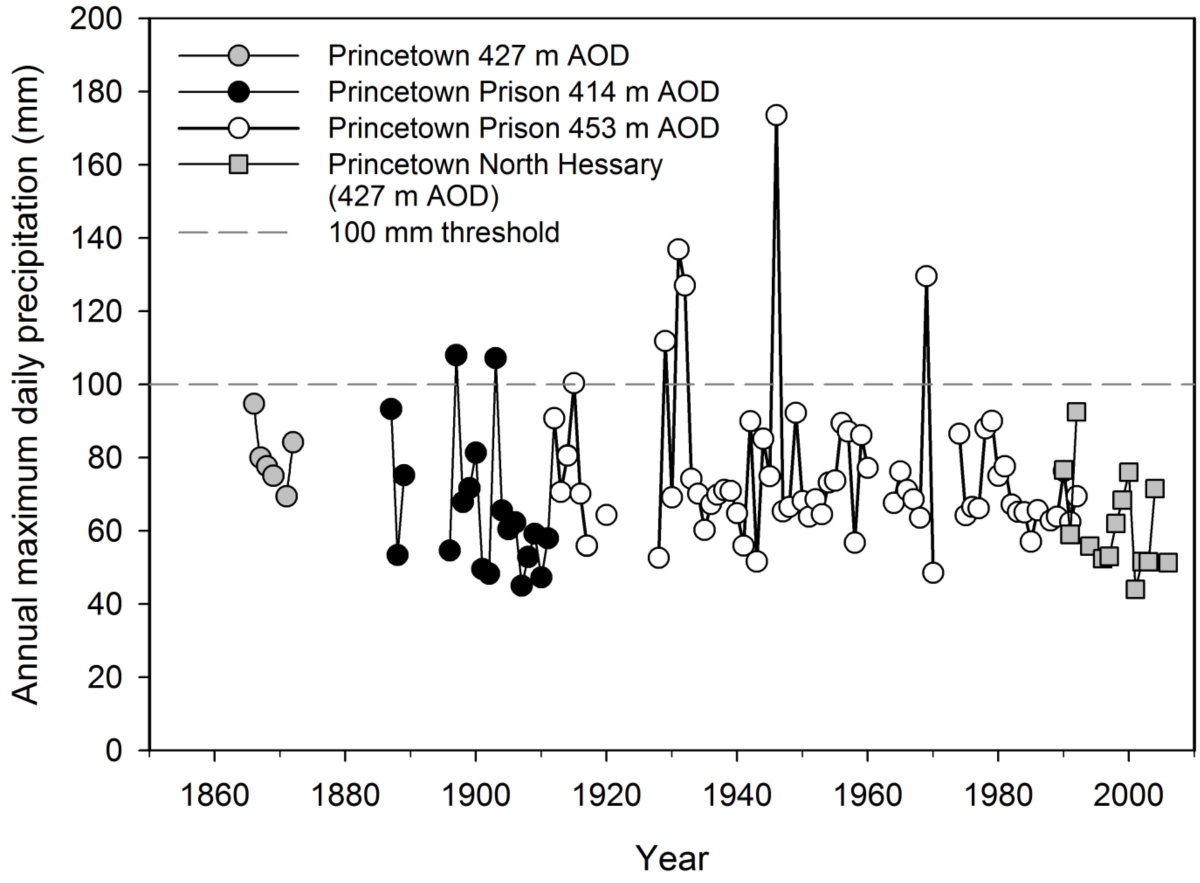

Figure 13. Summer (July-August) NAO data from 1850 to 2011 based on the index of Folland et al., (2009).

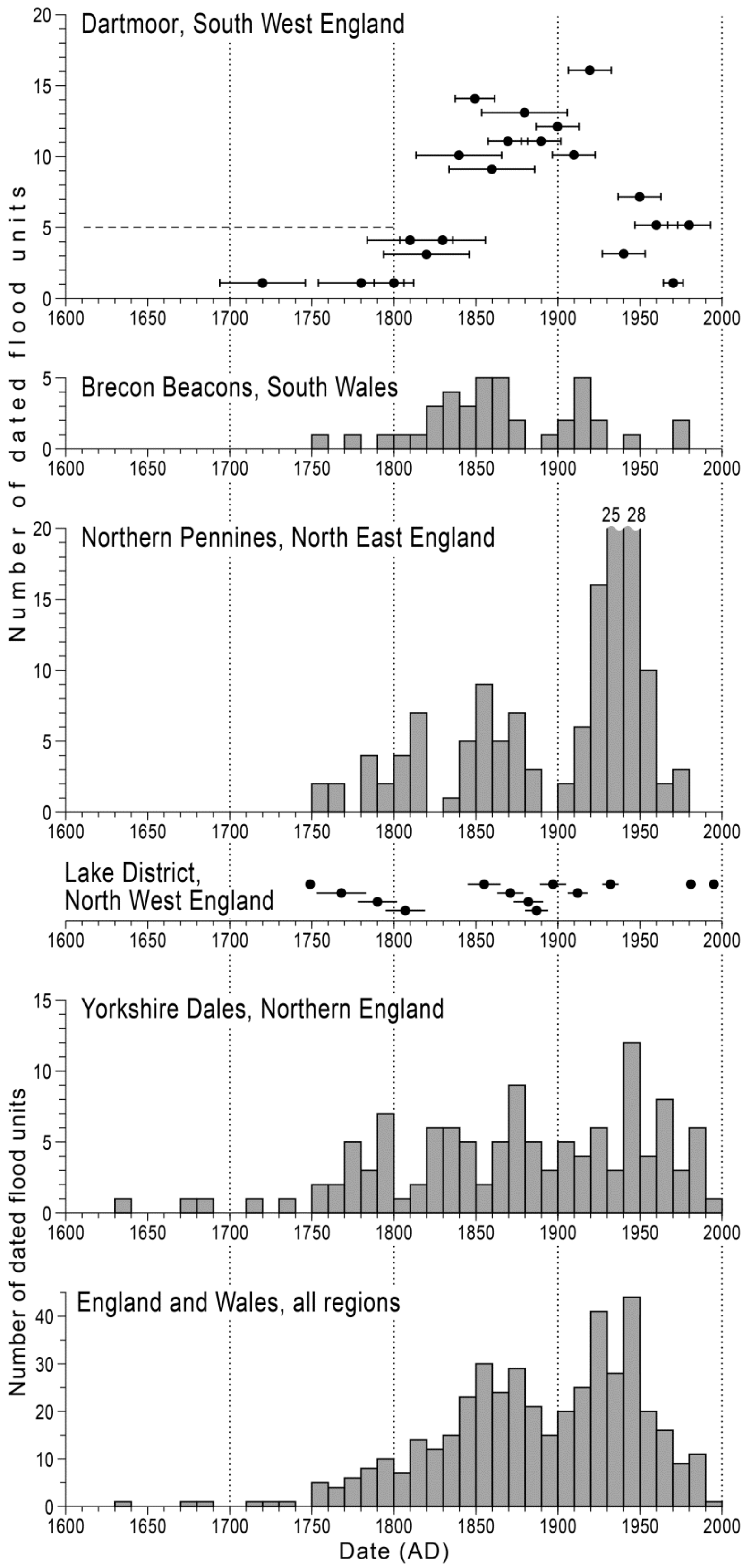

Figure 14. Decadal flood frequency plots of all lichen dated boulder-berms in England and Wales. This figure was first published in Macklin and Rumsby (2007, p. 174) and has been updated in this paper to include data from southwest England (the dashed line indicates low data quality/no data on Dartmoor associated with vegetated berms).

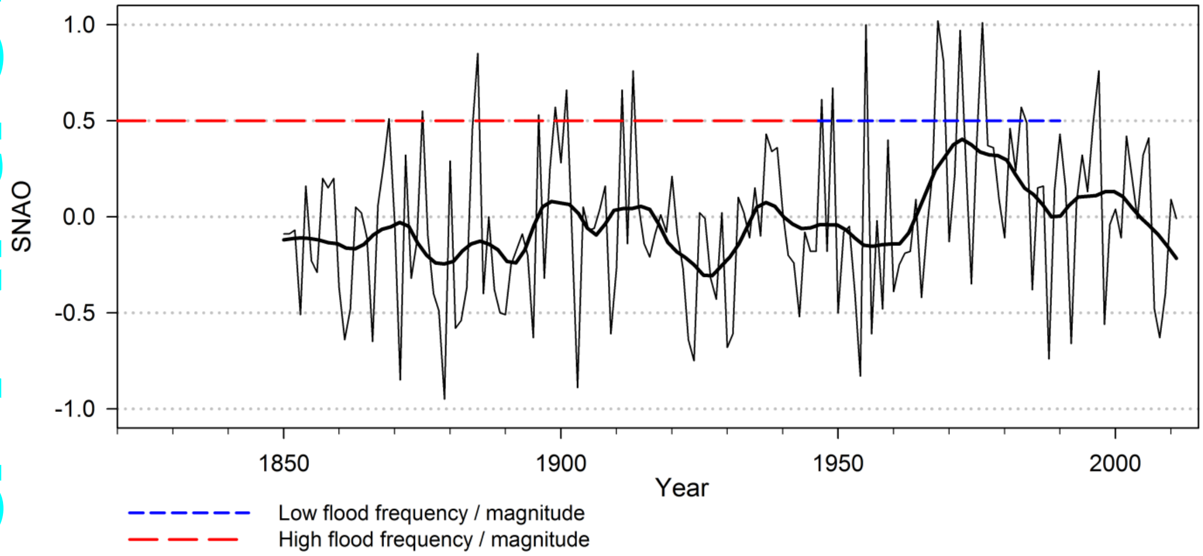

Figure 15. Decadal flood frequency of boulder-berms and annual maxima flow data for the River West Okement at Vellake gauging station, northern Dartmoor; upstream catchment area is ca. 13 km^2.

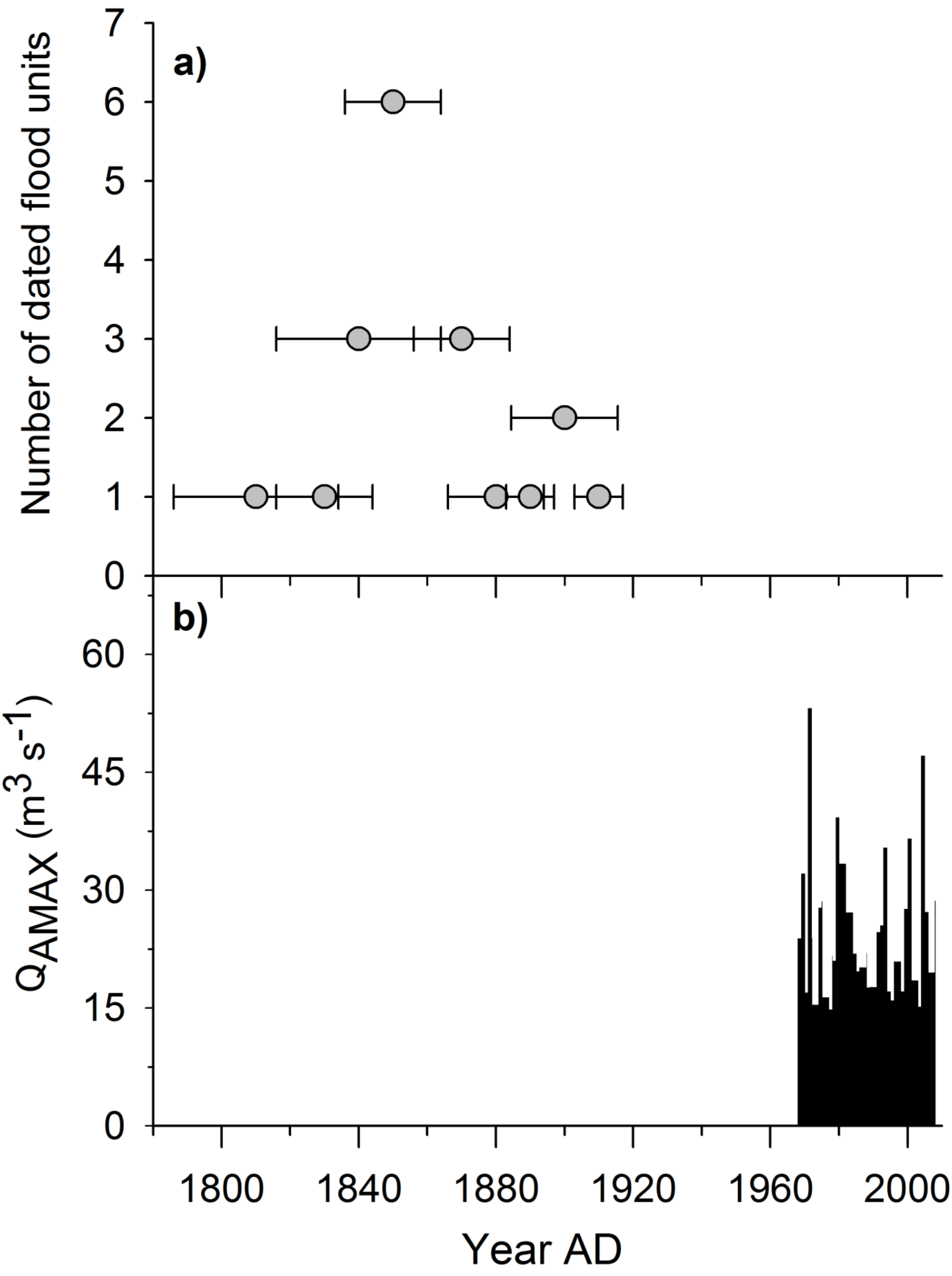

Figure 16. Specific discharge of annual maximum flows for rivers that drain Dartmoor and other notable extremes in the southwest of England.

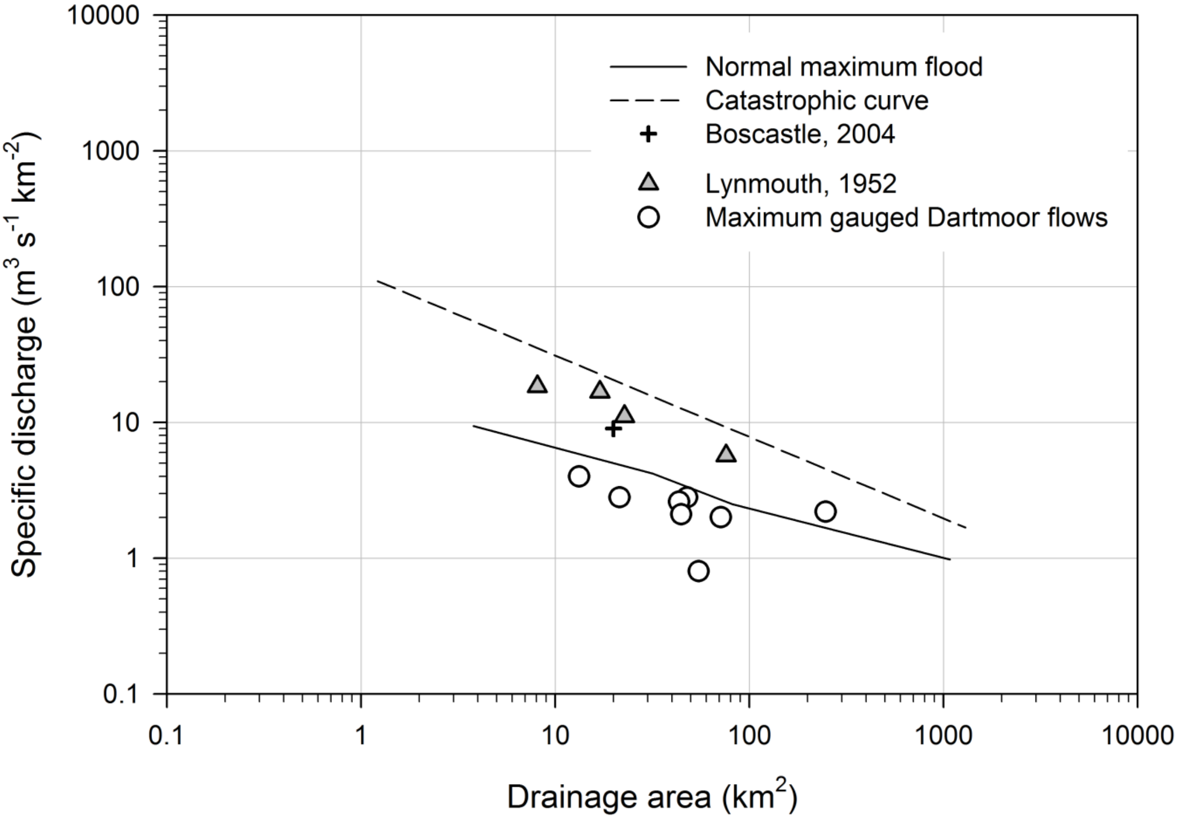

Table 1. Notable 20th century flash floods in Devon and Cornwall and monthly NAO Index values.

Location	Date	Rainfall (24 hr total)	Short duration rainfall	Flood damage	NAO	Reference
Lynmouth, Devon	15th August 1952	229 mm	ca. 135 mm in 5.5 hrs	Numerous houses and bridges destroyed. 34 fatalities.	-0.64	Dobie and Wolf (1953)
Camelford, Cornwall	8th June 1957	203 mm	ca. 138 mm in 2.5 hrs	Severe flooding on the River Camel. Bridges destroyed.	-0.64	Burt (2005)
Boscastle, Cornwall	3rd June 1958	No data	No data	1 fatality.	-0.98	Cornwall Council (2011)
Boscastle, Cornwall	16th August 2004	200 mm	ca. 181 mm in 4 hours	Over 70 properties flooded; bridges and buildings destroyed.	-0.28	Burt (2005); Roca and Davison (2009)

Table 2. Summary morphometric and boulder-berm data from study catchments on Dartmoor. *Denotes the presence of undated berms, due to vegetation growth. †Denotes uncertainty associated with a photographed berm deposited in 1956 or 1965.

Catchment grouping	Watercourse	Catchment	Area (km^2)	Reach channel slope ($m\ m^{-1}$)	Valley floor width (m)	No. berms	Record length	Largest dated flood	b-axis max.(mean) of largest flood (m)
Small (< 1.5 km^2)	Sniper's Gully	West Okement	1.0	0.153	10-15	4*	ca. 1840s - 1920s	ca. 1880s	1.20 (1.13)
	Deep Valley	Lyd	0.7	0.162	10-15	2*	ca. 1910s - 1980s	ca. 1910s	0.90 (0.82)
	E. Webburn trib.	Dart	0.7	0.161	10-15	1*	ca. 1890s	ca. 1890s	0.77 (0.76)
	Cocks Pit stream	West Okement	0.2	0.220	10-12	1*	ca. 1950s	ca. 1950s	0.33 (0.31)
	Manga Brook	North Teign	1.1	0.142	10-15	1	ca. 1920s	ca. 1920s	0.95 (0.72)
	River Tavy trib.	Tavy	0.7	0.179	10-12	3*	ca. 1780s - 1950s	ca. 1920s	0.82 (n/a)
	Lady Brook	Taw	1.4	0.164	15-25	7*	ca. 1820s - 1960s	ca. 1940s	0.90 (0.70)
	Braddon Lake	East Dart	1.3	0.067	10-12	1	ca. 1920s	ca. 1920s	0.61 (0.59)
	Middle Brook	Avon	1.3	0.093	15-25	1*	ca. 1860s	ca. 1860s	1.35 (1.12)
	Deep Swincombe	Swincombe	0.8	0.098	15-25	1*	ca. 1900s	ca. 1900s	0.91 (0.74)
Medium (≥1.5 - <10 km^2)	Doetor Brook	Lyd	2.2	0.080	10-12	3*	ca. 1860s - 1950s	ca. 1880s	1.40 (0.96)
	River Lyd	Lyd	4.9	0.050	30-50	3*	ca. 1820s - 1950s	ca. 1860s	2.00 (1.78)
	Red-a-ven Brook	West Okement	4.5	0.093	40-50	5*	ca. 1850s - 1950s	ca. 1850s	1.20 (1.05)
	Fishcombe Water	West Dart	1.7	0.155	30-40	3*	ca. 1840s -	ca 1880s	1.15 (1.01)

							1920s		
	Black-a-ven Brook	East Okement	3.5	0.107	30-40	7*	ca. 1720s - 1920s	ca. 1840s	1.55 (1.16)
	Blackaton Brook	North Teign	3.3	0.115	30-40	11*	ca. 1810s - 1910s	ca. 1880s	1.60 (1.20)
	East Dart	East Dart	9.0	0.060	30-40	6*	ca. 1860s - 1960s	ca. 1880s	1.06 (1.00)
	Plym	Plym	8.7	0.056	20-30	1	ca. 1980s	ca. 1980s	0.35 (0.34)
	Red Brook	Avon	1.7	0.131	10-20	3*	ca. 1830s - 1920s	ca. 1903s	1.08 (0.94)
	O'Brook	West Dart	4.8	0.065	40-50	1	ca. 1950s /1960s	1956/1965†	1.05 (0.93)
	Cherry Brook	West Dart	2.0	0.113	10-15	3*	ca. 1910s - 1960s	ca. 1910s	0.91 (0.85)
	Mardle	Dart	2.3	0.111	10-15	1	ca. 1940s	ca. 1947	0.60 (0.75)
Large (≥10 km^2)	East Okement	East Okement	10.3	0.072	50-100	10*	ca. 1800s - 1940s	ca. 1850s	1.15 (1.06)
	West Okement	West Okement	13.7	0.047	50-100	19*	ca. 1810s - 1910s	ca. 1840s	1.55 (1.08)
	Tavy	Tavy	24.3	0.035	50-200	27*	ca. 1850s - 1980s	ca. 1890s	1.87 (1.49)
	Taw	Taw	13.0	0.046	50-100	3*	ca. 1810s - 1910s	ca. 1810s	1.50 (n/a)
	North Teign	North Teign	21.1	0.050	50-100	7*	ca. 1800-1900s	ca. 1810s	1.51 (1.32)
	Erme	Erme	19.9	0.027	50-100	7*	ca. 1860s - 1920s	ca. 1860s	0.92 (0.86)

Table 3. Surface age predictions of granite gravestones, bridges and other monuments around Dartmoor calculated from regression equations shown in Figure 2. Mean and one standard deviation errors from true surface are 3 and 10 years (*P. tuberculosa*); 6 and 7 years (*R. geographicum*); 5 and 12 years (*P. corallina/ aspergilla*). Relatively few test dates are available for *R. geographicum* and *Pertusaria* species as they are less abundant on tombstones and the majority of data for these species were used to construct the original size-age graphs.

True gravestone/berm age (years)	Predicted gravestone/berm age (years)	Deviation from true age (years)
Porpidia tuberculosa (n = 22)		
50	48	-2
79	70	-9
58	59	1
11	9	-2
80	70	-10
95	114	19
17	16	-1
94	104	10
54	77	23
56	77	21
12	11	-1
27	25	-2
65	79	14
23	22	-1
24	32	8
27	16	-11
71	73	2
63	66	3
67	61	-6
74	79	5
87	88	1
1917 boulder-berm	1907	-10
Rhizocarpon geographicum (n = 5)		
94	97	3
80	87	7
100	107	7
121	137	16
1917 boulder-berm	1914	-3
Pertusaria corallina/aspergilla (n = 7)		
94	84	-10
62	68	6
106	116	10
81	72	-9
105	126	21
1917 boulder-berm	1928	11
Ditsworthy Warren House (late 18th/early/mid-19th century)	1801-1839	n/a

Table 4. Documentary history of major flood events on Dartmoor 1784-1992.

*Clapper bridges are relatively small structures made of split granite slabs laid horizontally over 1-2 central piers made of boulders.

Documentary flood date	River/ catchment/ general location	Flood description and impacts	NAO	Source(s)
July 1784	West Dart	Bridge at Two Bridges destroyed.	N/A	Horsham (2012b)
January 1823	Plym, Mew and Meavy	Rivers reached immense height.	-3.39	Crossing (1901)
August 1826	East Dart	Severe thunderstorm. Teignhead and Postbridge clapper bridges* destroyed.	N/A	Stanbrook (1994); Hemery (1978)
1830	Tavy	During the severe 1880 flood some of the older residents questioned whether the current level had exceeded the record of 1830. The majority view was that it had.	N/A	CBHE
August 1840	Dart	A wall of water rose up against the wedding party and washed the cart with groom and bride away to their deaths.	N/A	Manning-Saunders (1951)
October 1841	Burn, Taw	We understand the damage done was very considerable on the River Taw (in 1854), which has not been so high since the 16th and 17th October 1841.	-2.13	CBHE
June 1844	Ashburton	Rain lasted about an hour. The long-dry water courses could not carry the stream and the lower part of the town was flooded.	N/A	CBHE
August 1848	Dart	River (Dart) rose higher than ever known during the summer. A flood came down from Dartmoor with unusual rapidity.	N/A	CBHE
1854	Taw	See October 1841.	NA	CBHE
January 1866	Tavy, Walkham	To the numerous weather mischances of the week has to be added a destructive	2.06	Exeter & Plymouth Gazette (1866)

		inundation, which has torn up railways, washed away sheep and cattle, broken down bridges and caused great loss of property and human life.		
August/September 1873	Cowsic, Meavy	Clapper bridges washed away. One fatality.	-0.55	Horsham (2012b)
Summer 1878	Cherry Brook	Thunder and lighting. Cherry Brook rose rapidly….the storm continued to rage all the time with unabated fury.	-0.49	Crossing (1888)
July 1880	Tavy	Tremendous thunderstorm. The River Tavy rose higher than was ever known before. Three miners drowned.	-0.09	Crossing (1901); CBHE
July 1890	Tavy, Dart, Cowsic, Walkham, Taw	"The Great Storm". The River Tavy rose higher than 1880 and carried away several bridges. The storm began in Devon and Cornwall on the 16th, and produced great floods on the River Tavy and the other streams running off Dartmoor.	-0.63	Crossing (1901)
November 1894	Dart	The great flood of July 1890 was eclipsed by that of 14th November 1894. Rain all night – two flood peaks. Okehampton gas works flooded.	1.96	Burnard (1896)
February 1900	Dart, Okement	Wet and mild. A heavy snow storm on 13th, and an extraordinarily rapid thaw on 15th, flooding the river (Okement) to a great height. This flood was 2-3 feet higher than the hitherto record flood of 17th July 1890.	-2.36	Burnard (1901)
August 1917	Red-a-ven Brook, Sniper's Gully, West Okement, Fishcombe, Taw	Thunderstorm and flood. Extremely heavy rain which exceeded the limits of ordinary description. Rivers and streams turned to torrents.	-0.66	Worth (1918)
January 1927	Lyd / west Dartmoor	Heavy rain and widespread flooding on Dartmoor. The area around Lydford was particularly badly affected. Daily fall of 81 mm at Holne.	2.15	Dartmoor Archive; CBHE

November 1929	Dartmoor	Between 11th & 24th there were 4 daily falls in excess of 80 mm at Princetown (2 >90 mm). Two day total of 188 mm on 18th & 19th November. Daily falls of 107 mm and 112 mm in Aug & Oct of the same year.	2.15	Worth (1930)
August 1930	Southern & western Dartmoor	There was no outstanding rainfall day, but totals of 50-68 mm were sufficiently intense to bring down floods beyond normal.	-0.45	Worth (1931)
August 1938	Central and eastern Dartmoor	A great storm lashed the Moor. Two more bridges claimed. Greatest flood for 30 years. Daily fall of 62 mm at Princetown on 3rd.	0.46	Hemery (1978); Worth (1939)
November 1944	Avon	155 mm of rain fell in 36 hours. The River Avon was higher than in living memory and boulders weighing several tonnes were moved considerable distances. 7 day total of 318 mm at Princetown.	0.81	Worth (1945)
November 1946	Not stated	Record daily fall of 173.5 mm at Princetown and totals >120 mm at many other stations on Dartmoor.	-1.26	CBHE
1947	West Dart, Bovey	Dunnabridge bridge (timber) destroyed.	N/A	Dartmoor Archive
August 1959	Dartmoor	In a number of Dartmoor villages boulders rolled down the main streets with the rush of water.	0.33	CBHE
1956/1965 ?	O' Brook, Venford Brook	Horse Ford destroyed. Boulder-berm deposited and photographed at the time on O' Brook.	N/A	Hemery (1978)
June 1970	Plym	Women and children escaped death yesterday when the River Plym was swept by a wall of floodwater following a cloudburst. The drought-stricken river was transformed into a death-trap as thousands of tons of muddy water roared down the valley.	0.80	Horsham (2012a)

December 1979	Dart	Two day rainfall of 177 mm at Princetown with a max. of 90 mm on 26th.	2.07	BADC
November 1992	East Dart	On at least three occasions flood waters have either reached or flooded over the bridge spans (at Postbridge), in 1890, 1938, and 1992. 2-day total of 90 mm rainfall at Princetown.	4.52	Greeves and Stanbrook (2004)